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Public Health Service Assessment
Magnetic Resonance Imaging (MRI)
1985

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TABLE OF CONTENTS

	Page
Introduction	1
Background	2
Basic Principles of MR	2
Safety and Cost Considerations	8
Rationale	10
Review of Literature	11
Methodological Considerations	12
Clinical Applications	15
Head, spine and CNS	15
Thorax	36
Heart	41
Breast	44
Abdomen	44
Pelvis	55
Musculoskeletal system	61
Safety and Efficacy	66
Discussion	78
Summary	89
References	94

PUBLIC HEALTH SERVICE ASSESSMENT
MAGNETIC RESONANCE IMAGING (MRI)
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INTRODUCTION

Certain atomic nuclei, when placed in a static magnetic field, can be made to absorb or emit electromagnetic energy. This phenomenon forms the basis for proton imaging, which underlies the clinical technology of magnetic resonance imaging (MRI). Although the term nuclear magnetic resonance (NMR) was originally employed to describe this imaging modality, that term is now being superseded by the name MRI (1). Because images are formed without the use of ionizing radiation, the word nuclear was felt to be potentially misleading.

Proton MRI is a noninvasive method of graphically representing the distribution of water and other hydrogen-rich molecules in the human body. The procedure relies on the fact that the nucleus of hydrogen, a proton, has a positive charge and a spinning motion. This combination results in the creation of a minute magnet. When the human body is placed in a magnetic field of sufficient magnitude, the minute hydrogen proton magnets tend to align with the external field. When a second magnetic field is applied at right angles to the first, the protons tend to assume a new alignment at a higher energy state. With dissolution of this second field, the realigned protons will return to their original positions, releasing energy in the form of a radio-frequency (RF) signal. Once these RF emissions are received and processed by a computer, a graphic image can be constructed that will represent the substance being analyzed and the environment surrounding it.

BACKGROUND

The principle of magnetic resonance (MR) and the use of this phenomenon as an analytic tool in chemistry, biochemistry, and physiology has been recognized and developed since the 1940s. The first image created with magnetic resonance effects was produced by Paul C. Lauterbur in 1972 (2). The first human image that showed soft-tissue detail was produced by Mansfield and Maudsley in 1976 (3). The rapidity with which this technology has diffused as a clinical diagnostic modality has been exceptional. A survey conducted by the American College of Radiology predicted that more than 170 clinical MRI units would be operating in the United States by the end of 1985.

Basic Principles of MR

Magnetic resonance images appear similar in some ways to images produced by computed tomographic (CT) scans. However, because the physical principles of the processes are quite different, the information contained in the images differs significantly (4). Although the computer programs used to reconstruct the images are similar, CT scans are based on x-ray beam attenuation by an object, whereas MRI is dependent on a number of variables that may be combined in many ways to produce different types of information. Because of this factor, an MRI image is the result of a computerized image reconstruction algorithm designed to receive and analyze data in various predetermined ways calculated to best depict specific characteristics of the tissue being studied.

The creation of a proton MR image depends on four essential ingredients:

1. A static magnetic field of sufficient strength to bring about a slight magnetization of the hydrogen atoms in the body part being examined,

2. A sequence of RF pulses applied through a coil that surrounds the body,
3. A receiving coil to detect signals emitted by the sample when RF pulses are switched off, and
4. A computer to control generation of the pulses and process the resultant signals into an image.

The same coil may be used to apply the "driving" electromagnetic impulses and receive the signals generated by the sample.

There has been considerable variation in the magnets employed to produce the static magnetic field required for MRI. The strength of the magnets in clinical use around the world has varied between 0.02 Tesla (T) to 2.0T (1.0T = 10,000 Gauss). Their construction has been of three basic types: resistive, permanent, and superconducting. In general, resistive magnets have been used to achieve field strengths of up to 0.15T, permanent magnets up to 0.3T, and supercooled magnets for fields above 0.35T.

The stability and homogeneity of the magnetic field are important factors to be considered when selecting a magnet for MRI. Artifacts will result if uniformity is not maintained over the region being imaged.

Resistive electromagnets employ significant amounts of electric current to maintain a field and are water cooled to dispel heat from dissipated electricity. Their cost has been estimated at about $100,000. Operating expense is high because of their electric power consumption. Superconducting magnets employ a coil of tin-niobium alloy wires cooled to near absolute zero by liquid helium immersion. Once a magnetic field has been formed, they draw no additional electric power. Initial magnet cost has been estimated at over $200,000. Operating expenses include replenishment of the helium coolant, which may exceed $60,000 per year, but considerable progress has been made in techniques to conserve the gas. Permanent magnets require neither electricity nor helium, but in some designs their weight, which can reach 100 tons, can create siting difficulties. The initial cost of a permanent magnet is about $150,000, but operating expenses are very low.

Both resistive and superconducting units have fringe magnetic fields that surround them. These fringe fields have the potential for attracting stray magnetizable objects, disrupting cardiac pacemakers, and erasing magnetic tapes. Conversely, large masses of fixed or moving steel such as beams, elevators, or vehicles can distort the homogeneity of a magnet's imaging field. Stray RF fields can also degrade MR images. To avoid these disrupting influences the magnetic fields of MRI devices can be shimmed to achieve optimum uniformity, and shielding can be positioned to exclude external RF effects. A lively debate continues to surround the pros and cons of magnet selection. The reader may wish to consult references (3,5-7) for additional information.

In contrast to conventional radiographs or CT scans, in which the image is produced by a single tissue characteristic, MRI is capable of producing images by several techniques (4). In fact, various combinations of MR image production methods may be employed to emphasize particular characteristics of the tissue or body part being examined. The basic elements of MRI depend on the density of hydrogen nuclei (protons) in the object being examined, their motion (flow), and the relaxation times (T1 and T2) representing the period required for the nuclei to return to their equilibrium states in a strong static magnetic field after being subjected to a brief additional RF magnetic field perpendicular to the main field (8). These relaxation times describe the way that protons relinquish their energy after perturbation. They reflect the physical-chemical properties of tissue and the molecular environment of its hydrogen nuclei (2). Only hydrogen atoms are present in human tissues in sufficient concentration for routine use in clinical MRI. Although other atomic nuclei with odd atomic numbers (^{19}F, ^{23}Na, ^{31}P) exist in living tissue, their relative scarcity precludes medical imaging at this time, because they do not produce signals of sufficient intensity for routine clinical applications (9).

As noted, the net magnetization of a tissue's protons will lie in the same direction as the externally applied static magnetic field and will be the sum of magnetic moments attributable to the spinning of individual protons about their axes. These nuclear magnetic moments are not completely aligned with the external static field, but rather precess about its axis in a motion similar to that of a spinning top. Precessional frequency is a function of the intensity of the external magnetic field and the particular atomic nucleus being studied, in this case hydrogen. Precessional frequency is a characteristic of each nuclear species and varies linearly with the strength of the applied static electromagnetic field. Precessional frequency is also referred to as the Larmor frequency. When a perpendicular RF pulse at the Larmor frequency is applied to the precessing protons, there is resonant absorption of energy and net magnetic moments tend to be diverted from the parallel to a direction opposite to the orientation of the main magnetic field. They will also tend to assume a coherent pattern of precessional spins. Upon removal, the RF energy that was added at the Larmor resonant frequency is emitted by the protons in the form of a faint RF signal that can be detected by means of a suitable antenna coil. T1 (spin-lattice) relaxation time represents the resumption of net magnetization parallel to the longitudinal axis of the static field when the RF pulsating perpendicular field is removed. T2 (spin-spin) relaxation time represents the decay of transverse magnetization due to the loss of coherent precession after removal of the RF pulse.

Multiple pulse sequences are required to generate a usable MR image. Saturation recovery (SR), spin-echo (SE) techniques, and inversion recovery (IR) are the commonest sequences being employed in clinical practice. T1 and T2 relaxation times are the underlying rationale for these techniques. All three methods rely on application of repetitive pairs of RF pulses with acquisition of data (echo) after the second pulse. Pulses are designated "90 degree" or "180 degree" with respect to their capacity to deflect the magnetic moment of a proton from an orientation that is parallel to the external static field through a transverse state to an antiparallel orientation. The SR method consists of equally spaced 90 degree pulses which produce MR imaging signals that will vary with the T1 relaxation values of each region of the sample being studied. With SE sequences, a 90 degree RF magnetic pulse is followed by another of 180 degrees. Depending on the interval between sequence pairs (TR) and the interval between the 90 degree pulse and the peak of the echo (TE), SE methods can emphasize either T1 or T2 relaxation times. IR sequences employ repetitions of 180 degree pulses followed by 90 degree pulses. The images produced are weighted toward T1 relaxation times (8).

Signals dependent on T1 achieve their greatest intensity when this relaxation characteristic is shortest. This phenomenon can be explained by the rapid emission of absorbed RF energy when longitudinal recovery of net parallel magnetic moments is rapid. T1 is related to the molecular state of thermal equilibrium in a substance being imaged. Liquids tend to have shorter T1s than solids. Bone, with a long tissue T1 and few hydrogen atoms, will produce signals of extremely low intensity. In contrast, a long T2 will produce signals of highest intensity. T2 is influenced by the microenvironment of the tissue being imaged. Adjacent protons tend to dampen coherent magnetic resonance; as a result, the shortest T2s are found in solids (9). In general, T1 tends to emphasize the structural representation of a tissue, whereas T2 emphasizes distinctions between tissues.

Because the relaxation behavior of different tissues differs, investigators have exploited these distinctions to identify and to delineate tissues with MRI. Variations of relaxation times determine image contrast, so selection of an optimal RF magnetic pulse sequence in relation to a specific static field strength is very important in the clinical application of MRI. It has been noted, however, that apparent relaxation times may be technique dependent in as yet undetermined ways that render their use for measurement imprecise (2). Thus, signal strength for MRI is a function of proton density, a short T1, and an elongated T2. Fat generally produces stronger signals than other tissues; compact bone and air produce the faintest signals.

The formation of a spatially accurate MR image is based on combinations of static magnetic gradients of varying orientation that are designed to acquire information from selected points, lines, or planes within the body (2). Because the Larmor resonant frequency of a substance is proportional to the strength of the static magnetic field that is used, a superimposed uniform gradation of field strength will vary the frequency of the RF signal emitted by tissue protons dependent on their relative positions in the field. This principle permits the calculated acquisition of two- and three-dimensional data from a tissue being imaged by electronically adjusting the gradient orientation for the "slice" of clinical interest. The MRI tissue signals emitted may then be encoded so that their frequency spectrum corresponds to their spatial relationships. Because the range of the magnetic gradients is quite small, representing slight supplemental increments of energy to the main static field, any lack of homogeneity will produce spatial distortion in the MR image. Each variation from uniformity will cause an "erroneous" RF echo to be emitted, which the computer will attribute to an incorrect site. Thus, one of the most important considerations in MRI signal-to-noise ratios is the ability of the equipment to produce and maintain smoothly inclined electromagnetic gradients that permit the precise, spatially related emission of faint tissue signals. Various strategies have been employed to achieve these ends, and the design of image reconstruction techniques is of continuing technical concern. References (2,3) provide additional information about these matters.

Imaging times for MRI generally exceed those required for CT and other imaging technologies. Because the MR signals emitted by tissues are weak, excitatory pulse sequences must be repeated; the images represent a summation of the RF echo data produced. Because nucleii must be allowed to relax after each pulse in order for a signal to be emitted, there are severe limits to the rapidity of imaging. An MRI examination may consume from several minutes to more than a half-hour. Although certain sources of external RF and electromagnetic disturbances can be minimized by shielding and refinements of equipment design, living tissue itself is a source of noise and is considered to be a basic limiting factor to the reduction of imaging time (3). To reduce total imaging time, data from multiple adjacent tissue slices can be acquired simultaneously, but the required pulsing time per slice remains unchanged. Increasing the magnetic field strength also has permitted the shortening of imaging time, but the resultant requirement for proportionately higher Larmor resonant frequencies has been noted to produce attenuation of RF signals and phase shifts in body tissue (3,7,10). Thus, this approach also has its limits.

Safety and Cost Considerations

The safety of MRI has been an area of interest. Three potential sources of adverse effects have been identified: static magnetic fields, changing magnetic fields, and RF heating of tissues (11). The possible heating effects of MR on metallic implants and prostheses have also been mentioned (12,13). Patient anxiety, cardiac pacemaker function, and the difficulties of monitoring seriously ill patients connected to sensing and life-support equipment have been cited as well (14,15). Cautions concerning the use of MRI during pregnancy, particularly in the first trimester, have been expressed, but no existing data indicate specific fetal or maternal hazards (3). Most important, certain known risks of radiologic imaging are not present with MRI. No injectable or oral contrast media are routinely employed and no ionizing radiation is required.

The projected economic consequences of MRI have received considerable attention because of the high capital costs of equipment purchase and installation and the relatively low daily rate of patient examination capacity ("throughput"). Estimates of purchase price have ranged from $800,000 to more than $2 million, depending on field magnet type and size (16,17). Facility renovation and installation costs can increase the initial capital expense by from $80,000 to more than $1 million. Operating costs may range from $500,000 to $1.5 million annually (17,18). Estimates of costs per procedure, of course, depend on the equipment employed, the rate of patient throughput, and the complexity of the imaging examination. Charges are expected to range between $400 and $900 for each patient based on a 10-patient per day throughput rate (17,18,19). Increased operating hours might allow a greater number of patients to be imaged with a commensurate decline in per case costs, but the practicality of such a supposition rests on the availability of a pool of patients who might benefit from MRI. With the appearance of experimental, resistive, low-field MRI equipment in Europe, costs might fall. An MRI device with a field strength of 0.02T that is capable of head and body scanning has recently been reported (20).

RATIONALE

Magnetic resonance imaging is based on the physical-chemical phenomenon of nuclear magnetic resonance. Atomic nuclei with an odd number of neutrons or protons have magnetic moments because of their intrinsic spin. When such nuclei are placed in a strong magnetic field and pulsed with radio-frequency electromagnetic energy, they will resonate and emit a radio signal (3). The nucleus of hydrogen, one proton, is particularly suited to clinical MRI because of the ease with which it can be made to emit a detectable RF signal and because of its wide distribution throughout the body. The nature and duration of these emitted signals will be influenced by the strength of the static magnetic field, the chemical composition of the tissue, and the microenvironment in which it exists. Through a computerized process of generating pulsing sequences and the subsequent spatial encoding of resultant RF emissions, an image of the tissue being examined may be reconstructed. Such images differ significantly from conventional x-ray products in that they do not rely on relative attenuation of ionizing radiation. Image reconstruction can be accomplished in almost any plane; the signal data that are employed are emitted by the tissue being studied.

The ultimate aim of an imaging method has been stated to be "the differentiation of normal and abnormal tissue, preferably with as much specificity as possible" (21). Because MR images are produced from protons in the various tissues being examined, the technology possesses a unique capacity to demonstrate both structural and functional information of clinical importance.

REVIEW OF LITERATURE

The evaluation of a clinical imaging technology is an extremely complex matter. The first MR image of a body part was produced only in the late 1970s, and the first clinical trials of proton imaging began in 1980 (22). By November 1984, an MRI bibliography of 5,000 citations had been amassed (5). Unfortunately, all clinical studies to date have been uncontrolled. The technical adequacy of MR images, rather than their contribution to patient care, has received the greatest share of attention.

Two notable preliminary assessments of MRI have now been published. In September 1984, Steinberg, Kaiser, and Cohen issued their work for the Congressional Office of Technology Assessment (23). By January 1985, DiMonda had published an extensive American Hospital Association Guideline Report on MRI (17). In view of the comprehensive manner in which these authors have dealt with the basic background materials concerning MRI, the reader is referred to these two works and others for such information (2,4,8).

The advent of clinical CT scanning in 1973 aroused considerable interest in discovering the most appropriate, effective, and efficient (economical) diffusion and application of this expensive imaging technology. These same issues surround the current propagation of MRI. In July 1978, the American Journal of Roentgenology devoted its entire issue to an evaluation of computed tomography in its fifth year (24). It was estimated that 1,000 CT scanners had been placed in operation during these 5 years. Contributing investigators proposed strategies that offered promise for the scientific assessment of computed body and head tomography as well as for the achievement of optimum efficiency and efficacy in use. Although the proposed methodologies are in large part applicable to an evaluation of MRI, there is little evidence that these studies have significantly influenced the subsequent literature of CT scanning or magnetic resonance.

Methodological Considerations

Considerable attention has been focused on the choice of methodologic strategies to render a clinically useful MR image. Young has commented that the characterization of lesions by measurement of tissue relaxation time constants has been of particular interest (21). However, he states, the range of time constants associated with a tissue, be it normal or pathological, is large and complex. Because of this complexity, Young has reservations about the future of subtle pulse-sequencing methods designed to image specific nuances of soft-tissue composition. Expediency may favor the use of SR and SE techniques for structural depiction as the principal imaging tools. Hendee and Morgan have noted that the tailoring of scan sequences to particular clinical situations allowing the recognition of various disease processes represents a major area of current research (3).

Kramer has remarked that, according to existing data, the water content of imaged tissues is "the single most consistant contributor to observed differences in relaxation times of protons in tissue" (25). Both T1 and T2 relaxation times increase in proportion to the increasing water content of a tissue. He discussed the characteristics and potential applications of the three most common RF pulse sequences, SR, IR, and SE; he concluded that although MRI is sensitive to small changes in tissue physiochemistry, future applications require careful use of pulse sequences and methods to achieve MRI's full clinical potential.

The adjustment of MRI equipment in clinical use was addressed by Kneeland, Knowles, and Cahill (26). They emphasized that although these devices feature user-adjustable parameters such as RF pulse and magnetic gradient variations, these operations hold some potential for system misuse and resultant degradation of image quality. They urged that MRI data acquisition procedures be controlled by qualified persons.

Ortendahl et al covered the difficulty of evaluating imaging methodologies in normal subjects (27). These authors indicated that there is an almost infinite set of MR imaging techniques that may be used to detect and characterize disease. Thus, a truly exhaustive study of an individual patient becomes impractical. They suggest that the tissue characteristics of T1 and T2, proton density, and flow effects are the determinants of clinical efficacy at a given magnetic field strength. To the extent that the components and function of a tissue can be made manifest through these parameters, it is possible to identify optimal settings for the visibility of a disease by determining the greatest difference in the signal intensity of a lesion and its normal tissue background. They described a system of "tissue maps," based on actual patient data, which allows the observed contrast differences to be used in evaluating the efficacy of various MR imaging strategies and variation in magnetic field strength.

Other problems inherent to MRI concern the use of multisection techniques and section thickness; trade-offs involve imaging time, pulse duration, and the degree of magnetic gradients. Crooks et al discussed the importance of these relationships, (28,29) and, again, stressed the choice of imaging parameters in addressing clinical problems.

Because flowing liquids generally produce a low-intensity signal on MRI, there has been research interest in exploiting this phenomenon to measure blood-flow noninvasively. Only flow in larger vessels has been considered, because capillary blood perfusion of tissues has not generally lent itself to MRI. In theory, rapidly flowing blood leaves the body section being examined before a spin-echo has been emitted. The intensity of signals from circulating blood, however, depends on flow geometry and biophysical variables, which result in nonlinear data effects that impede accurate interpretation of the images produced. Three recent reports by Axel; Bradley and Waluch; and Moran, Moran, and Karstaedt have reviewed these problems (30-32). Although these investigators acknowledged the potential clinical importance of MRI blood flow measurement, they agreed that further experimentation and development were needed before clinical applications might be reliably attempted. Axel, however, emphasized the utility of MRI in visualization of normal and abnormal vascular structures and endorsed its use for the qualitative depiction of blood flow (30).

Surface-coil receiving antennas have been developed as a means of improving MR image resolution. This technique has revealed greater soft-tissue anatomic detail than is possible with other techniques (33). Instead of the usual coils of wire surrounding the patient's entire head or body, surface coils are small receiving antennas positioned over the specific body structure to be examined. An additional coil that transmits the RF pulsed magnetic energy to excite tissue protons may be included with the surface coil. Various configurations have been designed to conform to the body part being imaged. Improved RF coupling between the body and the antenna has been claimed, resulting in higher spatial resolution and sensitivity to signals (5). In general, surface coils have been best employed for structures close to their position. Coil radius is proportional to distance; smaller, closer loops achieve improved signal-to-noise ratios and higher sensitivity to signals. In the search for improved imaging, surface coils have been used to depict the orbit, breast, neck, and other regions (8,33).

Paramagnetic contrast media have been the subject of recent research. Weinmann et al have commented that the desire of investigators to distinguish between contiguous healthy and pathologic tissue, as well as between magnetically similar but histologically different tissue, have stimulated these efforts (34). MRI contrast agents have also been proposed as a method of evaluating organ function in renal disease, disruptions of the blood-brain barrier, inflammatory lesions, and other sites (35,36). The degree to which improved computer reconstruction of imaging data will render contrast enhancement unnecessary remains unclear (34,37-39). At the moment, contrast media development is investigational, and considerable animal experimentation is under way. The combination of tumor-specific monoclonal antibodies with paramagnetic contrast enhancement agents is also under study.

In vivo MR spectroscopy, the noninvasive measurement of relative concentrations of different nuclei in a tissue, is also the subject of current research. As already noted, ^{13}C, ^{19}F, ^{23}NA, and ^{31}P all emit detectable MR spectra. A "chemical shift" of RF resonance signal frequency occurs which theoretically permits the differential identification and monitoring of these substances in body parts (8,23). Such techniques require high-intensity static magnetic fields of exquisite uniformity.

Surface coils are frequently used for MR spectroscopy. Both Steinberg and Paushter consider in vivo MR spectroscopy to be promising but highly experimental. DiMonda has remarked that the extremely high field strength magnets required for spectroscopic imaging may place the position of 1.5T-2.0T devices in doubt for this purpose (17). The optimal unit for MR spectroscopy remains to be defined.

Clinical Applications

Head, spine and CNS. The use of MRI for the diagnostic evaluation of disorders of the central nervous system (CNS) has been rapid. An extensive bibliography, which largely covers the technical capacity of MR to visualize known lesions, is now available. Taveras has attributed the early adoption of MRI to the difficulty of examining the brain by external means, the fact that the brain does not move, and the frequent involvement of the brain in various pathological processes (40). Others have noted that the small magnet bore diameter of prototype devices permitted convenient experimentation only with the head and limbs. Bydder expressed the view that the specific contributions of MR to brain imaging are due to the absence of bone artifact when examining the posterior fossa, the high level of contrast seen between gray and white matter, and the availability of various imaging planes as well as various imaging techniques that can selectively enhance anatomic detail and pathologic change (41).

To avoid the pitfall of specifically selecting patients for MRI of the brain on the basis of known CT findings, Brant-Zawadzki et al studied the results of 70 consecutive cases that had received both procedures in a routine clinical setting (42). Focal brain lesions were found in 51 patients with either CT or MRI, or both. Diverse neoplastic, infectious, vascular, demyelinating, metabolic, and congenital disorders were represented. MR missed 3 of the 51 lesions, while CT missed 17 of the 48 lesions seen with MR. Different observers independently evaluated the CT and MR images, and their readings were compared with respect to the presence of a focal abnormality of tissue and their characterization of identified lesions. MRI was performed at 0.35T field strength with a typical acquisition time of 14 to 18 minutes. Optimal patient screening results were achieved using a spin-echo technique with relatively long pulse intervals that was T2 weighted (TR). The authors concluded that MRI appeared to be the "method of choice for initial screening of suspected brain disease." Lesions missed by MRI tended to be small or calcified. Specific histologic tissue identification was not possible. Knowledgeable correlation of clinical and physiologic information with the results of any imaging modality was considered fundamental to approaching a diagnostic problem.

Bradley and his co-workers studied the results of MRI and CT in 416 consecutive patients referred for evaluation of suspected disease of the brain or cervical spinal cord (43). Positive CT findings were not required for inclusion of a case. Three patients did not complete the MRI procedure because of claustrophobia, and 13 MR images were considered uninterpretable because of motion artifacts or other technical difficulties. Of the remaining 400 patients, 126 had no abnormalities noted with either CT or MRI. A total of 325 diagnoses were made in the 274 patients with positive findings by either modality.

The authors based their comparisons on a five-point "conspicuity index" in which class I lesions were normal on CT and abnormal on MR, and class V lesions were normal on MR and abnormal on CT. Intermediate classifications were based on the perceived specificity of lesions favoring either CT or MR. Overall, 129 of 325 positive diagnoses were made equally well with both imaging techniques. MR was abnormal in 93 cases where CT was normal, whereas CT was abnormal in only 3 cases where MR was normal. Among the intermediate cases, MRI was the preferred modality in 68 cases and CT in 32. The lesion that was most often more readily identifiable on CT was meningioma. Each patient was the subject of an average of 2.5 MRI acquisitions; various pulse sequences and imaging planes were used to "optimize discrimination of suspected disease." A 0.35T static magnetic field with multislice imaging achieved a 7mm slice thickness.

Bradley et al concluded that MRI had a clear advantage over CT. They found that only three small meningiomas had been totally missed by MRI. Moreover, they considered MRI superior to CT in the detection of multiple sclerosis, subcortical arteriosclerotic encephalopathy, posterior fossa infarcts and tumors, small extra-axial fluid collections, and cervical syringomyelia. The limitations of CT due to bone artifacts when imaging lesions of the brainstem and cerebellum were noted. Conversely, where calcifications are of significance, such as in the diagnosis of meningiomas, Bradley et al preferred CT. Although the results of this study favor MRI, Bradley et al added that CT should be used to study patients who exhibit claustrophobia, are likely to move, require life-support devices, or are best evaluated rapidly; thus they considered MRI and CT complementary.

In an effort to systematize detection of lesions of the head with MRI, Droege, Weiner, and Rzeszotarski developed a mathematical model to optimize lesion visibility by means of gray-scale manipulations based on the relationship between tissue and machine characteristics, and their effect on MR pulsing techniques (44,45). Although their computer simulation methodology is beyond the scope of this assessment, the authors made several important points about the clinical use of MRI. Gray-scale ordering on CT scans of the head is constant and familiar; bone exhibits the brightest image, followed by gray matter, white matter, cerebrospinal fluid, fat, and air. Because the gray-scale ordering of MRI is highly variable, it is potentially confusing and difficult to interpret. The authors found that MRI is unique because gray-scale order can be manipulated to remedy problems of lesion visibility and to enhance the brightness of specific normal or pathological tissues. Freedman, Stephens, and Fisher had identified the process of selecting an appropriate MR pulsing sequence as an important determinant of patient throughput, and thus, of the ultimate cost of MRI (18). Droege and his colleagues proposed a strategy for MR imaging based on the combination of a spin-echo sequence followed up, if necessary, with an inversion-recovery sequence. On the basis of their preliminary experience with 190 patients, they found that only a few predetermined sequence sets are required for most head studies. Identification of lesions was improved by increasing the contrast-to-noise ratio between the lesion and surrounding brain tissue. The investigators employed data from a variety of lesions but did not directly address the specific diagnostic effectiveness of MRI. They stressed the importance of recognizing abnormal anatomical patterns, rather than simply the detection of lesions, because accurate diagnostic interpretation is the objective of an imaging procedure.

The ability to image the pituitary directly with MRI has been established. Kaufman recently reported visualization of the gland in 100 percent of 380 subjects studied using a 0.3T unit and a slice thickness of 12mm (46). Pictorially better results were reported in a smaller number of patients imaged in a 1.5T unit using a 7mm section. The hypophyseal stalk and pituitary lobes were visualized in 13 of the 15 patients examined. Pituitary abnormalities are manifest as size and shape variations or changes in tissue character. Because small lesions (microadenomas) or minimal enlargement may be difficult to discern on MRI as well as on CT, Kaufman commented that the succession of these procedures, as the initial or complementary study, for imaging the pituitary remained to be determined. Nevertheless, he stated that MRI would be the procedure of choice in evaluating pituitary disease because it has the unique ability to image both anatomic definition and tissue character. The use of the higher magnetic field strength of 1.5T was considered preferable, but 0.3T images were thought to be clinically practical for routine applications.

Bilaniuk also compared high- and low-field MRI of the pituitary in six patients with clinical and CT evidence of pituitary abnormality (47). He reported that high-field MR at magnet strengths of 1.0T to 1.5T produced superior results when compared with low-field images made at 0.12T. They described delineation of pituitary masses with good rendition of detail and took particular notice of the improved visibility of the optic nerves, chiasm, and visual tracts. These structures are not normally seen with CT techniques, because contrast media diffusion may be blocked by space-occupying lesions. The author concluded that high-field MR scanning should become the procedure of choice in the evaluation of pituitary lesions. He also noted that criteria for the diagnosis of pituitary microadenomata have not yet been determined for MR, whereas they are already established for CT imaging. Low-field MRI at 0.12T was considered the least effective in demonstration of lesions.

Bilaniuk et al also studied the use of high- and low-field MRI in a group of 16 patients with known cerebral abnormalities previously diagnosed with CT scans (48). Eight of the cases involved the sella or pituitary; the remainder were in other cerebral sites. High-field MRI, at 1.0T to 1.5T, was found to equal CT in the identification of lesions. Soft-tissue contrast and accurate delineation of pathology were considered superior with MR. Low-field MR, at 0.12T, was judged to be less satisfactory, but objective scientific proof was impossible.

Twenty-six patients with primary brain tumors present on CT images or suspected on clinical grounds were selected by Brant-Zawadzki et al for evaluation with both 0.35T MRI and CT scan (49). Ten patients had gliomas; the remainder had various other lesions. In 16 of the 26 patients, MR provided additional information to that obtained with CT, whereas in 3 cases it was less effective. Three patients with nondiagnostic CT images were more adequately examined with MRI. Inability to identify foci of calcification was considered a major limitation of MRI. Difficulty in separating tumor from surrounding edema was noted with both procedures. The authors predicted that MRI would supplant CT as the imaging modality of choice for diagnosis of CNS neoplasia. The advantages of MRI they cited include elimination of the need for ionizing radiation or intravenous contrast agents; improved sensitivity in detecting pathologic alterations of normal tissue; and better depiction of tumor extent and associated structural abnormalities. MRI also offers improved planning of biopsy, surgical resection, and radiation therapy.

In a study of 33 patients with cystic intracranial lesions evaluated with both CT and MRI, Kjos et al were able to distinguish and categorize the lesions best with MR (50). Images were made with a 0.35T field using multisection spin-echo technique. By comparing the intensity patterns of cyst contents, it was possible to categorize these lesions into three basic groups corresponding to cerebrospinal fluid, tumoral and inflammatory, and hemorrhagic or colloid. MRI helped the investigators narrow the differential diagnosis and plan case management. An MRI screening procedure for visualizing cystic brain lesions was proposed for future clinical use. Particular success was noted in MR imaging of cystic abnormalities of the posterior fossa, because the bony artifacts that obscure CT views of this area could be avoided.

Lee et al reported similar results in the imaging of posterior fossa abnormalities with MR (51). Forty patients with a variety of suspected lesions that had received CT scans were subsequently given MR scans of the posterior fossa. A 0.5T magnetic field was employed with spin-echo and some inversion-recovery sequences that provided an MRI slice thickness of 10mm. The authors commented that previous work with MR imaging of posterior fossa lesions had emphasized diagnosis of neoplasms. Their series included not only tumors but also congenital malformations, atrophy, ectasia, cysts, aneurysms, hematomas, hydrocephalus, and multiple sclerosis. In general, independent reviewers considered that 13 lesions were demonstrated on MRI only, 24 were better demonstrated on MRI but also seen on CT, and 3 lesions were better seen on CT. The major advantages of MR over CT were stated as the absence of bone artifacts, an increased sensitivity in detecting tissue contrast differences, and the ability to obtain direct sagittal views. Determination of the histologic nature of tumors and differentiation of them from surrounding edema were seldom possible. They concluded that MRI was often superior to CT scanning with contrast media in the diagnosis of posterior fossa lesions.

MR imaging of the skull base has been reviewed by Han and his co-workers (52). They performed MR scans in 54 patients who had previously received other radiologic procedures. A 0.3T field strength unit was used with various pulse sequences giving a section thickness of 12mm. Selection of MR imaging planes was based on the location of pathology already seen on previous radiography. Han et al commented that because the skull base contains bone, soft tissue, fluid, fat, and air "in every possible juxtaposition," it represents a "stringent test" of MR as an imaging system. The authors concluded that MRI holds a significant advantage over CT in evaluation of compartments that are surrounded by dense bone such as the posterior fossa, but that the inability of MR to display fine bony detail may be a drawback in circumstances where its visualization is diagnostically important. The authors predicted that MR will become the primary imaging modality in evaluation of the posterior compartment including the clivus and craniovertebral junction. They also judged MR to be superior to CT in imaging soft-tissue structures of the nasopharynx and skull base. Because MRI has direct multiplanar capability, they emphasized its use in providing additional information about the "exact location and extent of disease" not available from CT.

Further experience with imaging of brainstem disease has been reported from Cleveland and New York. Hueftle et al reviewed MR and CT scans of 26 patients with the established or suspected diagnosis of brainstem glioma (53). They achieved complete sensitivity in correctly identifying 11 gliomas and complete specificity in excluding 6 patients without gliomas. The remaining cases were of other lesions. Because metastases, other tumors, and infarcts could not be distinguished from gliomas, they recommended that MRI be the primary examination modality for all cases of clinically suspected brainstem glioma, with CT used as an adjunct if further delineation is required.

Lee and his associates also reported their experience with MRI of brainstem tumors in 18 patients (54). A 0.5T unit was used with various pulsing sequences and with single as well as multislice techniques. Section thickness was 8mm. MRI was able to detect tumor enlargement of the brainstem in all cases; CT, in only 13 of 18 patients. The distinction between primary and metastatic lesions could not be drawn. The authors noted a lack of correlation between the margins and configuration of brain lesions on MR images in relation to clinical manifestations of the tumors--a possible effect of neoplasm merging with edema on the images. They concluded that MRI is superior to CT in evaluating brainstem tumors.

Han et al have summarized their experience with MRI in pediatric cerebral abnormalities (55). They found MRI to be more advantageous than CT in 23 of 105 cases, equally beneficial in 76, and not equal to CT in 6, in which calcifications in brain or tumor tissue were missed. A wide variety of lesions were represented in this series, with from 1 to 12 cases in each of 19 categorical groups. Patients studied were limited to those with positive CT findings or those of "clinical concern" with normal CT scans. These researchers made several significant points: Because 75 percent of pediatric cerebral tumors occur below the tentorium, the effectiveness of MR in visualizing the posterior fossa is of recognized importance. Although sedation may be required for young patients, the multiplane imaging capability of MR diminishes the need to manipulate their position. Finally, with the removal of the necessity for ionizing radiation and injectable contrast media, the medical and surgical treatment of pediatric cerebral disorders may be followed up more closely with less risk. A particular pediatric abnormality, agenesis of the corpus callosum, has commonly been diagnosed using a variety of radiologic techniques. Davidson, Abraham, and Steiner, using a 0.15T MRI unit, have reported that MR is the procedure of choice, "if not the only necessary" procedure, for this disorder (56). Because myelin exhibits high tissue contrast, relatively small structural abnormalities were said to be detectable.

The use of MRI for evaluation of clinical stroke syndromes has been tentatively addressed by DeWitt et al (57). Although they made no effort to compare radiographic techniques with the results of MRI, they collected three-dimensional data using a 0.147T magnet and slice thicknesses of 1mm to 10mm that could be matched with CT scan information later. They described various pulse sequence strategies and discussed their experiences with the measurement of tissue T1 and T2 characteristics. They noted that more work was required on the role of MRI in the diagnosis of stroke disease and the pathophysiological mechanisms of cerebral infarction and ischemia.

A study of MRI in patients with chronic seizure disorder, who had normal neurological examinations and normal CT scans, was reported by Laster and his colleagues (58). They remarked on the increasing role for MRI, in preference to CT, in detecting demyelinating disease and primary brain tumors. Laster selected 34 patients who had had seizures over the last 5 years and who had manifested no abnormalities on previous neurological and CT examinations. Surgical lesions of "potentially therapeutic significance" were discovered with MRI in 4 of these cases (12 percent). CT detection of structural brain anomalies in equivalent patients with idiopathic seizures was stated to be about 1.0 percent. An MR device of 0.15T field strength was used, and 10mm slices were made in the transverse, sagittal, and coronal planes. Multislice technique was used in some, but not all, cases. Laster et al suggested that MRI be the imaging method of choice in "cases of chronic and presumed cryptogenic epilepsy," citing its value in visualizing surgically correctable lesions.

CT scanning has been dominant in the evaluation of head trauma from a very early date. Attention has now shifted to possible applications of MRI in this area. Han et al as well as Sipponen, Sepponen, and Sivula have reported their results with MRI in small numbers of patients with previously diagnosed traumatic cerebral lesions or chronic subdural collections (59,60). Because chronic hematomas become of equal x-ray density as brain tissue, their depiction with CT may be difficult. MRI will exhibit distinct differences in tissue contrast depending on the nature and composition of a cerebral collection. Both groups of investigators saw potential for MRI in the evaluation of head trauma, but considered further research into the identification of appropriate patients to be important.

In addressing MRI of the neck and spinal column, Han, Benson, and Yoon noted that it has the unique property of "directly imaging the brainstem, spinal cord, and midline ventricular system in continuity in a single sagittal plane" (61). Stark et al described the anatomy of the neck and thoracic inlet employing MRI under normal and pathologic conditions (62). The superior capacity of MR to detect soft-tissue contrasts enables all the contents of the neck, with the possible exception of cortical bone, to be viewed in a unified manner without the use of x-ray or contrast media. Stark and his group made MR images of the neck in 10 normal subjects and 14 patients with various known thyroid, parathyroid, and surgical lesions. A specially designed RF coil was employed in a 0.35T imaging system. They found that the limited resolving power of MRI was a problem in detecting thyroid and parathyroid lesions and that no tissue discrimination between malignant and benign lesions was possible. The authors described their work as preliminary. Normal anatomical structures could be routinely imaged.

Multiple sclerosis (MS) is a demyelinating disease of the central nervous system that may consist of widely divergent lesions that vary in location as well as in time of onset (63). Maravilla et al stated that the diagnosis of MS has traditionally been one of exclusion, requiring the use of multiple imaging studies including CT and myelography when spinal cord lesions were suspected. A battery of nonimaging clinical studies has been used to confirm the diagnosis of MS. The accurate localization of lesion distribution is important in establishing the extent of disease and its prognosis. Because MRI permits the continuous visualization of the intraspinal contents, the cervicomedullary junction, and the structures of the posterior fossa, it is potentially well suited to evaluating disorders such as MS that affect diverse levels of the central nervous system (61).

Runge et al have reported using MRI in 42 patients with the clinical diagnosis of multiple sclerosis (64). They employed seven different MR scanning techniques to assess the relative efficacy of various pulse sequences matched to patient characteristics. In all cases, multiple neurologic events separated by anatomic site and time had been recorded. MRI was accomplished on a 0.5T unit with 10mm slice thickness. They developed a scale for rating disease severity with MRI based on the size, number, and definition of lesions that were visualized. Clearly defined abnormalities were detected in all cases of MS examined with MRI. Thirty-three of these patients were given CT scans, with and without contrast media, within 2 weeks of their MR scan; only 15 (45 percent) of the 33 CT examinations were positive. Milder forms of the disease tended to remain undetected by CT techniques.

Runge et al also found that the characteristic abnormalities of MS seen on MRI tended to be more extensive than those seen with CT. Lesions of MS were generally imaged as areas of low signal intensity in contrast to normal surrounding white matter. The image could be reversed so that the lesions appeared as bright areas. Changes on MRI considered indicative for MS included the abundance of discrete lesions, the distribution of demyelinized plaques, the asymmetry of involvement, and a "lumpy-bumpy" pattern adjacent to the lateral ventricles. Caveats expressed by the authors included the lack of autopsy evidence of correspondence between MR-imaged MS lesions and the histologically confirmed location of plaques, as well as the possible need to distinguish between MS and deep white matter infarcts in the elderly. The authors concluded that "MRI seems to be the method of choice at present for the diagnosis and evaluation of multiple sclerosis."

Maravilla et al have imaged MS plaques in the cervical cord, a development that complements research by Runge et al (63). CT scans have not been able to depict MS lesions in the brainstem, cerebellum, optic nerves, or spinal cord. Twenty-one patients with clinical and laboratory evidence of MS were studied with MRI. All exhibited characteristic cerebral MS plaques. By using a 0.35T system with an RF head coil, multislice technique, and 7mm section thickness, it was possible to demonstrate typical findings of MS plaques within the cervical spinal cord in 10 (48 percent) of the 21 patients. The MRI signal characteristics were similar to those seen in the brain. Maravilla et al commented that it has not yet been possible to distinguish between the demyelinating lesions of acute and chronic MS plaques. They added that MRI detection of MS in the brainstem and posterior fossa is already possible, but the examination of the orbits, lower cervical cord, and spine requires further research with surface RF coils that might permit thinner slices at improved signal-to-noise ratios.

Jackson et al have reported a prospective study of 32 patients with MS which compared the sensitivity of lesion detection and location by neurologic examination, CT scan with contrast media, and MRI (65). They stated that the symptoms of MS are variable and transient, posing diagnostic difficulties in many patients. More than 250,000 Americans are afflicted, and MS has been described as the most common disabling neurologic disease of young adults. CT imaging has been an important tool for confirming the presence of demyelinating plaques within the CNS. On the basis of their review of reported studies, Jackson et al noted that CT imaging of plaques has generally been positive in only 13 to 49 percent of clinically "definite" cases, 11 to 20 percent of "probable" cases, and 0 to 22 percent of "possible" cases. The use of double-dose, delay-enhanced CT has reportedly increased the yield of detected lesions three- to fourfold.

Thirty-two patients with suspected MS were evaluated by a neurologist and classified as definite MS (25 patients), possible MS (4 patients), and probable MS (3 patients). The cases were also characterized as acute or chronic.

The results of CT scanning with delay-enhanced contrast were compared with MRI on a 0.14T unit using spin-echo techniques and 10mm section thickness. In the 25 cases of definite MS, MRI detected lesions in 19 (76 percent) cases, while CT was positive in 15 (60 percent) cases. For cases classified as acute, the techniques were of similar sensitivity, 65 percent and 60 percent, respectively. In chronic progressive MS, MRI was positive in 75 percent of cases, whereas CT was successful in 20 percent. Because many of the imaged MS lesions were asymptomatic, there was little correlation between their location and the localization of clinical neurologic manifestations. Lesions of the posterior fossa were more likely to be seen with MRI than CT. However, Jackson et al noted, MS lesions in that area need be only a few millimeters in size to produce significant symptoms. Their detection with CT is frequently impeded by bone artifacts, and MR visualization may be obscured by volume-averaging effects. Of five patients clinically classified as definite MS, all had lesions of the posterior fossa, optic nerve, spinal cord, or combinations of these sites. The authors concluded that MRI was at least as sensitive as delay-enhanced CT in detecting MS plaques, and was superior in demonstrating chronic demyelination.

Han, Benson, and Yoon listed several advantages of imaging the spinal column with MRI (61). The ability to depict the entire cord and its relationship to structures of the posterior fossa have already been mentioned. Neither contrast media nor ionizing radiation is required, and the ability to perform MRI on an outpatient basis is an added benefit. Traditionally, myelography, as an inpatient procedure, and CT, with and without contrast materials, have been employed to image the cord, nerve roots, and vertebrae. As in the case of other applications of MRI, Han, Benson, and Yoon stated that the selection of appropriate pulse sequence techniques is crucial to the successful depiction of specific normal and pathological conditions of the spine. Because MR imaging of the craniovertebral junction is simplified in comparison with traditional radiographic modalities and myelography, these investigators considered MRI the examination of choice for a wide variety of neoplastic, structural, and surgical applications in that region (61).

On the basis of their experience with MRI in 13 patients with surgically proven syringomyelia or hydromyelia, Pojunas et al reported generally satisfactory results (66). Using magnetic fields of 0.5T to 1.3T and section thicknesses of 10mm to 14mm, they detected 11 of the 13 cystic lesions. They concluded that "MRI is the imaging modality of choice to screen and follow cases of syringo- and hydromyelia because it is noninvasive and usually accurate." If the diagnosis is in doubt because of atypical clinical or MRI features, they suggested conventional radiographic studies as followup procedures.

Paushter and Modic have reviewed spinal MRI and found that its contrast resolution was superior to that of CT and that the axis of imaging could be varied in multiple planes without the image deterioration that occurs with CT (67). These investigators also noted the absence of ionizing radiation and the absence of the need for contrast agents. They emphasized careful choice of pulse sequences to avoid masking pathologic conditions and discussed the merits of various pulsing strategies. They found T1 weighted images to produce the best general anatomical delineation. The choice of imaging modality for the intervertebral discs is a particularly important problem. The authors stated that the normal nucleus pulposus contains 85 to 90 percent water, whereas the annulus fibrosus contains about 78 percent water. By optimizing the contrast differences between these tissues based on their water content using a T2 weighted image, it is possible to differentiate between them. The authors commented on the easier differentiation between annulus and nucleus in the lumbar region compared with differentiation between cervical and thoracic discs, which are smaller in volume. With aging, the water content of the two tissues becomes equal, which permits the differentiation of degenerated discs from normal ones. These authors stated that because herniated discs generally degenerate soon after displacement, lack of visible degeneration on MRI usually precludes a diagnosis of herniation.

Extradural defects impinging on the subarachnoid space caused by displaced disc material also may be visualized with MRI. Because MR allows the sagittal depiction of several vertebral levels simultaneously, Paushter and Modic found it useful in the localization of disc degeneration and possible herniation. They stated that CT generally provides its best results in the axial plane, with other views considered less satisfactory. The authors also stated that direct visualization of nucleus pulposus herniation in the axial plane is best accomplished with CT scanning, which can produce thinner slices. They pointed out the difficulty of distinguishing degenerated discs from vertebral bodies with MRI in the axial plane. According to these investigators, MR imaging of spinal tumors, both intramedullary and extradural, lesions of the vertebrae, and soft tissues was considered well established. The accuracy of MRI in demonstrating the level of spinal block by space-occupying lesions was stated to be equal to CT with the use of intrathecal constrast media above and below an obstruction. Hemangiomas as well as primary or secondary neoplasms of the vertebrae were said to be easily visible with appropriate pulse sequences. In addition, diagnosis of disc-space infection may be an area where MRI surpasses CT. Spinal trauma with bony impingement on the cord can frequently be depicted. Paushter and Modic concluded that "MRI has already become the procedure of choice, when available, in the diagnosis of Chiari malformation, syringomyelia, tethered cord, degenerated disc, and disc-space infection," but that it could not substitute for more conventional imaging techniques in evaluating bony degenerative abnormalities. They suggested that decrease in slice thickness and improved signal-to-noise ratio were important correlates of further advances in MRI of the spine.

Modic and his colleagues have reported their efforts to standardize the examination of intervertebral discs (68). Sixty-five patients--20 normal subjects and 45 with known or suspected disease of the lumbar spine--were studied. Eight had degenerative disc disease, 27 had both degeneration and herniation, 5 had stenosis of the spinal canal, and 5 suffered from disc-space infections. The results of MRI were compared with conventional radiographs, high-resolution CT scans, and myelograms. Evaluation of MR images was rated between 0 (nondiagnostic) to 3 (providing information not obtained from conventional studies). Using MRI, the investigators identified degenerative disc disease in 6 of 20 normal patients. They concluded that MR is the most sensitive method of identifying this condition. As already noted, the absence of degenerative disc changes would exclude all but the acute stage of herniation. In a subgroup of 17 patients with herniated discs studied with a modified MR pulsing technique and both sagittal and axial images, MRI was equal to the sensitivity of CT and myelography in detecting the herniation. MRI was equal or superior to radiographs, CT, and radionuclide studies of disc-space infections, and was generally equal to myelography and CT in imaging stenosis of the spinal canal. CT was better at distinguishing bony from soft-tissue impingement. The investigators reasoned that the principal limitations of spinal MRI include "section thickness, spatial resolution, examination time and lack of signal from cortical bone." Its advantages stem from the fact that MRI is "an accurate, noninvasive means of evaluating intervertebral disc disease which can be performed on an outpatient basis." They found that the pulsing modes described permitted identification of lumbar degenerative changes and document herniation, canal stenosis, and disc-space infection. These findings agree in all major respects with those of Han, Benson, and Yoon (61).

Maravilla et al also have studied the comparability of MRI and CT scanning in specifically identifying and characterizing lumbar disc abnormalities (69). Eighteen patients with known degenerative disc disease, selected on the basis of abnormal CT findings at one or more vertebral levels, were imaged with both MR and CT. The CT images were generally multiple transaxial slices, with angled sections in a few cases when such views were deemed necessary. MR images were made on a 0.35T unit using multislice techniques that provided 7mm section thickness. Actual MR data acquisition time varied from 4.5 to 17 minutes depending on the pulse sequence employed. Sagittal views were routinely made with transaxial and coronal images to supplement the data when needed. Total MR study time for each patient including positioning, ranged between 45 and 90 minutes.

The investigators evaluated the results of all procedures independently, employing prospectively defined clinical diagnostic criteria. Surgical verification was obtained in 5 of the 18 cases. The basis for comparison was a diagnosis of lumbar disc disease based on CT scanning, with differentiation of herniation, disc bulge, and normal discs accorded principal emphasis. Maravilla et al found that MRI and CT have equal sensitivity for detecting disc herniation, but that MR was more sensitive in revealing abnormal discs. Because MRI permits examination of the entire lumbar spine as well as the intrathecal space and conus, its sensitivity for detecting abnormalities was quite high. CT was more specific for the type of disc pathology and determination of its site. The investigators concluded that CT remained the preferred primary method of evaluating the lumbar spine, but MR was a useful complement in the diagnosis of degenerative lumbar disc disease. They considered appropriate candidates for MRI to be patients with indications of an intrathecal, lower spinal cord, or conus medullaris abnormality, as well as cases in which postoperative scarring or equivocal CT findings did not permit accurate diagnosis.

MR imaging of the cervical spine has been studied by Hyman et al (70). Fifty patients with clinically suggestive indications of lesions in the upper spinal canal were examined with 0.6T MRI. Their results were compared with available radiographs as well as with results from CT, CT with metrizamide contrast, and myelograms. Various MR techniques were used including single and multislice, head and body RF coils, and selected pulsing schemes. Section thickness was 10mm. Lesions were classified into intramedullary, intradural/extramedullary, and extradural. Of the 50 patients, 38 had 40 distinct lesions, and 12 had no identifiable cervical abnormalities. It was found that MR "was consistently, better than routine CT scanning in the detection of lesions of the spinal cord and in directly imaging the effects on the spinal cord of extrinsic abnormalities." No advantage of myelography or CT with metrizamide over MRI was found for the diagnosis of intramedullary lesions. For extramedullary abnormalities, all modalities were useful but MRI was noninvasive and did not involve ionizing radiation. Among the cases of extradural abnormalities, MR proved to be more sensitive to disc degeneration while myelography was the preferred method of detecting and evaluating herniation of the nucleus pulposus and its effects on nerve roots.

The authors made a point of emphasizing the value of MRI in providing clinically significant information about cortical and medullary bony structures, despite the inability to detect direct signals from cortical bone. Metastases as well as other soft-tissue changes relating to skeletal integrity or structure were usefully visualized. The authors compared MR imaging pulse sequences for the applications that were studied, and offered recommendations for their clinical use. They found that MR of the cervical spine was "the procedure of choice, after plain radiography, when disease of the cervical spinal canal is suspected." They recommended CT and myelography for cases in which MRI examination is unrevealing.

Similar results with MRI in a case of thoracic spinal echinococcosis have been reported by Mikhael, Ciric and Tarkington (71). Although the disease is relatively rare in the United States, the patient had involvement of the upper dorsal spine with vertebral destruction, paraspinal soft-tissue overgrowth, and compression of the cord. It was found that MRI could depict the typical multiloculated lesions, delineate the spinal cord, and evaluate the extent of the disease. MRI was suggested as a replacement for myelography and CT for the prolonged followup of such cases.

Twelve patients with a variety of nasopharyngeal diseases, ranging from neoplasms to muscular atrophy, have been examined with MRI, and the results compared with images from 30 normal subjects (72). Dillon et al used a 0.35T unit with spin-echo sequence techniques to produce 7mm slices. Acquisition time was 34 minutes to gain 15 successive sections. They found that MR routinely produced images of normal and pathological soft tissue structures in greater detail than CT scans of the same patients. A role for MRI was recognized in diagnosis and treatment planning among patients with nasopharyngeal disease as well as retropharyngeal and cervical extensions of such lesions.

The application of MRI in a small series of three patients with acoustic neuromas of the internal auditory canal was studied by Daniels et al (73). Radiographic procedures employed for such studies involve invasive gas cisternography or contrast media. The investigators found that MR could demonstrate early enlargement of the 7th and 8th cranial nerves in the internal auditory canal with little interference from adjacent bone.

The application of MRI to evaluate the eye and its innervation has been studied by several groups. In vitro demonstration of changes in the vitreous body progressing from gel to liquid that simulate degenerative states were reported by Gonzalez et al (74). Han et al reported their preliminary experience with MRI in 11 patients with space-occupying lesions of the orbits (75). They concluded that bright signals from adjacent retrobulbar fat caused an inability to visualize the margins of cortical bone and blurring of small soft-tissue structures. Because of involuntary eye movements, the long data acquisition time required for MRI may also lead to motion artifacts. The advantages of MRI of the orbit were found to be its multiplanar capability, which permitted precise definition of relationships between masses and normal soft-tissue structures. The investigators expressed the opinion that MRI offered no distinct advantage over CT beyond the absence of ionizing radiation.

Li et al have reported similar results with MRI in 15 patients with space-occupying orbital lesions that were also studied with CT and ultrasound (76). These investigators used a 0.15T imager using both spin-echo and inversion-recovery pulses and a slice thickness of 10mm. Axial MR scans were performed; supplemental coronal and sagittal views were taken when needed. Diagnoses were confirmed surgically in 12 cases, on clinical grounds in one, and by orbital venogram in another. All orbital lesions were well demonstrated with MRI, but the investigators concluded that spatial resolution was superior with CT. Ultrasound was found to be a rapid, inexpensive method to demonstrate intraocular structural disruptions as well as to provide data that permit the categorization of lesions based on their acoustic textures. Imaging of periorbital structures, or those at the orbital apex and wall, may be difficult with ultrasound. Li et al noted the risk of cataract formation that accompanies repeated x-ray exposure of the lens; this represents a limitation on the use of CT for frequent followup studies. MRI was found to offer no advantage over combined CT and ultrasound in the diagnosis of orbital tumors. It was considered better than ultrasound, but not equal to CT in depicting the structural details of lesions. The absence of ionizing radiation was viewed as the major strong point of MRI.

Daniels et al have reported on MR imaging of the optic nerves and chiasm (77). Four normal volunteers were compared with four patients with tumors. Diagnoses were based on clinical, radiographic, and CT findings, with surgical verification in two cases. Their findings were preliminary. MRI was considered effective in demonstrating the optic nerves, but the most common tumors had "relatively little contrast with respect to the optic nerves." The use of newer thin section MRI techniques and surface coils, currently under development, may enhance the capacity of MRI to detect orbital and optic nerve pathology (28,33).

In research into the technical aspects of head and CNS imaging with MRI, investigators have been working to improve tissue contrast and resolution and to achieve noninvasive tissue diagnosis by employing calculated differential tissue relaxation times (78-81). Histologic diagnosis with MRI represents an added dimension of research that is beyond the scope of this assessment.

The advantages of low magnetic field strength in attaining good spatial and contrast resolution of the brain were the subject of a report by Seppanen, Sippanen, and Sivula (20). They stated that their results were adequate for anatomic localization and lesion detection in six patients examined with a prototype 0.02T unit. They considered the clinical information they obtained to be "at least equal to that of x-ray CT."

The progress of MRI of the CNS was reviewed by Kucharczyk et al (82). They concluded that pulse sequences have been defined that permit efficient screening for disease. They estimated multislice study of the brain or spinal cord to take between 13 and 17 minutes, generating 20 consecutive sections that are 10mm apart. Each change of plane requires a repetition of the process. The usual patient examination was said to consume "less than half an hour." In all, MR was judged to be more informative than CT and equally efficient for diagnosing CNS disease. MRI was stated to be superior to CT in detecting lesions and in characterizing such processes without known biologic hazards. Limitations of MRI included the thickness of imaging slices and the inability to depict calcifications and cortical bone. The problems posed by patients with implanted magnetic materials or requiring life support systems were noted. In summary, Kucharczyk et al found that the accumulated evidence to date supports MRI as the imaging modality of choice for screening patients with suspected disease of the CNS. Specifically, they found that MRI was useful in the diagnosis of "neoplasm, ischemia, hemorrhage, infection, and degenerative and demyelinating diseases." Bydder has generally concurred with these opinions of cerebral MRI and has stated that future improvements will likely come in the areas of speed, ease of operation, reliability, and efficiency (41).

In a retrospective review of the first 1,000 patients who received MRI examinations at the Mayo Clinic, Baker et al reported that 740 of these persons were thought to have head, neck, or neurologic disease (83). A 0.15T unit was used with whatever pulsing sequences were considered appropriate for each case. Slice thicknesses ranged between

5mm and 20mm. A study protocol was not involved and the patients were variously imaged with CT, myelography, or other modality in accord with the clinical judgment of their physicians. Overall, MRI was considered superior to CT and myelography for the detection and characterization of most lesions of the head, neck, and CNS. Disadvantages included inability to depict calcifications or distinguish between new and old bleeding. Motion artifacts and poorer spatial resolution than CT were regarded as significant factors in some cases. The ability to obtain views in multiple planes, the absence of bone artifacts, as well as the marked sensitivity of MRI to minimal tissue alterations were thought to compensate for any such drawbacks.

Thorax. Thoracic applications of MRI have generally been reported in terms of specific lesions rather than in terms of the capability of the modality to assist in the clinical evaluation of diagnostic problems. Cohen has noted that the ability of MR to obtain coronal and sagittal images as well as the cross-sectional views usually associated with CT enables the acquisition of tissue and structural data not available by other means (84). Although Cohen was cautious in his evaluation of coronal and sagittal MR thoracic views, O'Donovan et al believed that these planes were well suited to the vertical orientation of mediastinal viscera and vessels, facilitating comparison with the results of conventional radiographic images (85). By examining 27 subjects with coronal MRI and 12 with sagittal MRI, the investigators were able to demonstrate significant features of normal thoracic anatomy as well as typically encountered pathology of the pleura, pulmonary parenchyma, mediastinum, and hila. O'Donovan et al concluded that these views should be considered future conventional planes for MRI of the thorax.

Webb et al reviewed the results of coronal thoracic spin-echo multisection MR images obtained from 10 normal subjects with views from 20 patients with various abnormalities (86). These coronal results were then compared with transaxial views of the same patients. A 0.35T system was used and cardiac gating was performed in four normal and three abnormal subjects. It was possible to depict the mediastinum from the level of the ascending aorta or main pulmonary artery anteriorly to the mediastinal portion of the right pulmonary artery or tracheal corina posteriorly in a series of five coronal sections. Sixteen of the 20 abnormal patients had a mediastinal, hilar, or thoracic inlet mass, while the remaining four had lesions of the lung parenchyma. CT scans were available in 15 of these subjects. Webb concluded that coronal MRI of the thorax can be helpful in contrasting mediastinal masses with fat but should always be used with transaxial MRI because this latter view was generally equal or superior for defining pathologic areas. Both Cohen and Webb et al agreed that coronal MRI of the thorax may be helpful when a specific need for this view exists, but transaxial scans were generally more useful (84,86). Both groups confirmed the ability of MRI to produce accurate images of normal and pathological mediastinal structures.

A retrospective study by Epstein and his associates evaluated the results of MRI in 45 patients with known or suspected mediastinal disease, 30 of whom also had CT scans (87). MRI was accomplished with a 0.12T unit using serial sections of 13mm thickness. Typical data acquisition time was about 2 to 4 minutes per slice. Various pulsing schemes, both T1 and T2 weighted, were used without cardiac or respiratory gating. Of the 30 patients with CT scans, 20 received intravenous iodinated contrast medium. Pathologic verification of lesions was available in 34 patients with "a strong presumptive clinical diagnosis in the remaining 11 patients." Bronchogenic carcinoma and lymphoma were the most common lesions, accounting for 15 and 9 cases respectively. The balance ranged from pneumonia and aortic aneurysm to esophageal lesions, with from 1 to 4 patients each distributed among 10 additional categories. Transaxial MRI detected lesions of the anterior mediastinum in 17 cases, lesions of the middle mediastinum in 18 cases, and lesions of the posterior mediastinum in 5 cases. Eight patients demonstrated normal thoracic anatomy. In the 30 patients with both CT and MRI, 20 (66 percent) were considered to have had new information provided beyond that already available from conventional radiographs. CT was rated superior to MRI in 6 patients (20 percent) and

MRI was superior in 5 patients (16.7 percent). The two modalities were stated to be of equal clinical utility among the remaining 19 cases. The authors concluded that MRI can provide excellent cross-sectional images of the mediastinum without intravenous contrast medium or ionizing radiation. Bone, which does not image well with proton MR, was predictably not well visualized in this series, but excellent differentiation of fat and vessels from solid mediastinal masses and lymphadenopathy was reported. Overall, the investigators noted that MR produces greater soft-tissue contrast in the mediastinum than CT images. This advantage was considered to compensate for MRI's lower degree of spatial resolution. Mediastinal MRI with a 0.12T field was found to be comparable in image quality to third-generation CT, with no need for x-rays or contrast medium.

Similar results have been reported by Baker et al among 51 patients with various chest lesions (83). They found that MRI could distinguish hilar nodes and mediastinal tumors from large vessels more easily than CT could do without contrast enhancement. Because no ionizing radiation is required, Baker et al concluded that MRI "has become an important procedure for screening pediatric patients with mediastinal widening or suspected lymphoma, thymoma, or vasuclar anomalies in the thorax." Cohen also found that MRI was particularly useful in examining the hilum and that other mediastinal regions can be successfully imaged (84).

Heelan and associates compared CT and R wave cardiac gated MRI in 20 patients with primary carcinoma of the lung (88). Hilar and mediastinal examinations were interpreted blindly and the results matched with findings at surgery and histologic data. Intravenous contrast material was used for CT scans. MRI was performed on a 0.5T system which acquired 8 slices 12mm to 15mm thick simultaneously. Both CT and MRI were quite similar in their ability to depict enlarged nodes and tumor in the hila and mediastina of these patients. True positive readings were made among all 14 cases of hilar involvement and among all 10 cases of mediastinal involvement with both imaging methods. There was a slightly higher number of false positives--7--with MRI, compared to 5 with CT. All these cases were found to have enlarged benign nodes greater than 15mm in size.

A similar prospective study was conducted by Webb et al in 33 patients suspected of having bronchogenic carcinoma (89). Cardiac gating was not employed for MRI data acquisition. Contrast agents were used in all but one CT procedure. The authors concluded that MR "can be considered equivalent to CT in the detection of most intrathoracic abnormalities of importance in the staging of bronchogenic carcinoma." Enlarged nodes and direct tumoral invasion of the mediastinum by a hilar or mediastinal mass were equally demonstrated by both modalities. Hilar adenopathy was reported to be shown better with MRI.

Levitt et al compared MRI and CT for staging proven bronchogenic carcinoma in 37 patients (90). The hila and mediastina were examined with gated and ungated MRI and intravenous iodinated constrast-medium-enhanced CT. It was found that cardiac gating was not a requisite for high-quality MR images. Both CT and MRI results were interpreted with knowledge of prior radiologic and bronchoscopic tests. Standard criteria for resectability/nonresectability were employed to stage hilar and mediastinal lesions. CT staged 35 of 37 patients correctly, and MRI was correct in 36 of 37 cases. The authors concluded that CT remains the procedure of choice for staging bronchogenic carcinoma and evaluation of hilar or mediastinal lesions because of certain MR pitfalls they identified. These pitfalls included poor imaging of small nodal calcifications and false positives due to volume averaging and misinterpretation of esophageal soft tissue, as well as long data acquisition times. Because MRI was helpful in revealing vasculature without contrast agents, Levitt et al suggested its use in patients with possible allergy and for diagnostic problems not solved by CT.

The diagnosis of thoracic aortic dissections is an application of MRI that has received considerable recent attention. Amparo et al successfully used MRI to demonstrate and categorize dissections in 100 percent of 13 patients known or suspected to have that condition (91). Depiction of the intimal flap and determination whether the dissection extended into the ascending aorta was possible in all 13 cases. An MR unit of 0.35T field strength was used with spin-echo sequences to produce a series of transaxial images encompassing the top of the aortic arch to the diaphragm. Imaging time was reported as 17 minutes for thoracic procedures, with an additional 17 minutes required if the abdominal aorta was visualized. The authors emphasized that a surgical decision in patients with aortic dissection is based on involvement of the ascending aorta. Injection of contrast material is required to make this determination with CT or aortography. They suggested that MRI can be the initial imaging procedure when aortic dissection is clinically suspected and "that the information provided by MR is sufficient to manage many cases."

Geisinger et al also demonstrated and categorized thoracic aortic dissections in six patients, with cardiac gating employed in five (92). They reported that transverse, coronal, and sagittal views were used to advantage in depicting the relationship of the aortic arch vessels to the dissection. Imaging was done on a 0.6T unit using multisection technique and a slice thickness of 7.5mm. Scan time was between 30 and 60 minutes per patient. Several advantages of MRI over CT and arteriography were discussed. If the information obtained from MRI demonstrates a Type B dissection, with no involvement of the ascending aorta, arteriography could be averted. Many patients have underlying renal pathology, which makes use of contrast medium with both CT and arteriography hazardous. The ability of MR to produce direct multiplanar views was also noted. Geisinger et al concluded that MRI "should become an important imaging modality in the evaluation of aortic dissections."

Cohen has concurred with the findings of Amparo et al and Geisinger et al based on a review of thoracic MRI (84). He remarked that "MRI may become the method of choice for evaluating dissecting aortic aneurism, especially in stable patients." Amparo, Higgins, and Shafton have provided an interesting addendum by reporting their success in diagnosing a case of aortic coarctation using both transaxial and sagittal MRI images in a manner similar to the techniques employed for dissections (93).

Heart. The use of MRI for cardiac imaging depends on the difference between signals received from myocardial tissue and those from flowing blood (94). To avoid motion artifacts, cardiac gating techniques have been used to control MR pulse sequence timing and thus acquire both anatomical and functional information. Both electrocardiographic (ECG) and finger plethysmographic linkages have been used to trigger MR sequences, but ECG R wave methods have now prevailed.

Higgins and his colleagues have reviewed the literature concerning cardiovascular MRI and Higgins' own studies of cardiac applications (95-97). They reported general success in the MRI detection of a variety of congenital and cardiovascular anomalies in 22 patients compared with 16 normal subjects (95). The ages of the patients ranged from 2 months to 75 years and all had been diagnosed previously. Catheterization and angiography had been used in 21 cases and a chest x-ray in 1 case. Although normal breathing was undisturbed and not linked with gating, the younger patients were sedated. MRI was accomplished on a 0.35T unit by performing multiple sections of 7mm thickness in each patient. Pulse sequences were ECG-gated to the R wave. In all subjects, images gated to every heartbeat were obtained. Three multislice series were done in each patient, which took 30 to 45 minutes of imaging time. Images included the heart from the great vessels to the apex. Most sections were transverse, although in some cases coronal and sagittal sections were made. Overall, transverse MR views were adequate to reveal pathology, but cardiac valves were not successfully seen in most patients by any method. Because blood flow ordinarily produces a weak MR signal, structural features of the heart and great vessels were emphasized, although they noted that slowly flowing blood or specific gating procedures can produce a confusing intraluminal image. Gating was considered essential for cardiac MR imaging. Higgins et al concluded that MRI holds promise for "direct tissue characterization, noninvasive blood flow measurements, and assessment of myocardial metabolism in vivo," but that they could draw no conclusions about the clinical efficacy of MRI in the small number of patients they had studied. Higgins and his colleagues have since reiterated the opinion that there has been too little clinical experience with MRI in cardiovascular diagnosis to predict its ultimate clinical role (96,97).

Soulen, Stark, and Higgins have subsequently published their work in five patients with suspected constrictive pericardial disease (98). Gated MRI was performed; transverse sections were obtained in all patients and additional coronal slices in three. The authors stated that it is clinically necessary to distinguish between restrictive cardiomyopathy and constrictive pericarditis, because the latter condition is surgically correctable. Pericardial thickening was 5mm or greater in all these patients and was successfully diagnosed without difficulty. It was found that MRI "appears to be the noninvasive method of choice for the diagnosis of constrictive pericardial disease."

Dinsmore et al have discussed the ease with which ECG-gated MR images of the heart can be obtained (99). They studied 10 patients and an equal number of normal subjects for the purpose of defining the planes of optimal display for future cardiac MRI applications. They found that the conventional transverse, coronal, and sagittal views orthogonal to the chest do not coincide with the cardiac axes. They proposed a series of three standard planes that best fulfill the needs of cardiac diagnostic imaging.

Reasoning that MRI can distinguish between cardiovascular and nonvascular mediastinal structures, Amparo et al employed ECG-gated MRI to study cardiac and paracardiac masses (100). A 0.35T MR unit was used with spin-echo pulse sequence repetition time determined by the R-R interval of each heartbeat. CT, angiography, and echocardiography have been used to evaluate masses associated with the heart, but the authors found that gated MRI was uniquely able to provide cross-sectional views of the chambers, myocardium, pericardium, and great vessels without contrast medium or x-rays. Direct coronal and sagittal imaging was noted as another advantage of MRI. The investigators were able to determine whether the masses were intracavitary, intramural, or paracardiac in nine cases, and they excluded the diagnosis of cardiac tumor in one case. On the basis of these preliminary findings, they considered MRI to provide "as much information as echocardiography, CT, and angiography combined in the evaluation of cardiac and paracardiac masses."

Eleven young patients, between the ages of 1 to 21, who had undergone palliative systemic-pulmonary shunt procedures for congenital heart defects were evaluated with ECG-gated MRI by Jacobstein et al (101). There were 17 surgical shunts present in the 11 patients, and MRI successfully depicted 11 of these (65 percent). The authors generally found the MRI contrast between vessel walls and flowing blood to be excellent. The depth of the shunt within the body did not compromise visualization, as is the case with ultrasonography. Overlying lung or bone did not impair MR imaging of the shunts. They concluded that gated MRI "is the only noninvasive imaging technique currently capable of visualizing palliative systemic-pulmonary artery shunts with a high degree of success."

Whereas many researchers have employed ECG-gated MRI to avoid motion artifacts and to provide functional cardiovascular information, Choyke et al have worked with nongated cardiac MRI (102). Thirty-four patients with various cardiac diseases were imaged on a 0.12T unit using spin-echo sequences with a very short echo time (10 to 20 milliseconds). The technique was considered promising, since information was obtained that might be sufficient for screening or diagnostic purposes under some circumstances.

Lieberman, Botti, and Nelson, in summarizing cumulative experience with MRI of the heart, have concluded that it remains a research technique (94). They acknowledged, however, its particular utility in examining the hila, regions of the mediastinum, and dissecting aortic aneurysms. Paushter et al have considered gated MRI to be very promising for noninvasive anatomic and physiologic evaluation of the heart, especially with respect to congenital defects (8).

Breast. MRI of the breast has received attention as a noninvasive method of diagnosing cancer without the use of ionizing radiation. Kopans, Meyer, and Sadowsky reviewed the subject of breast imaging and concluded that this use of MRI should be considered experimental (103). They noted that detailed breast images had been made, but long scan times and lower spatial resolution compared with x-ray modalities limited MRI's utility for this purpose. If, however, MR tissue diagnosis of malignancy becomes possible, they foresaw a greater role for its application. Kopans has reiterated those opinions in another review (104). He stated that although high-resolution surface coil MR equipment might improve breast imaging, its cost and cross-sectional imaging nature would preclude generalized use.

In an initial trial of MR breast imaging, 71 patients with mammographic or physical evidence of breast disease were studied by El Yousef and Duchesneau (105). Their work was done on a 0.3T unit using both body and surface coils and various pulsing protocols designed to depict and characterize breast lesions. They concluded that although the future role of MRI for diagnosis and screening of breast disease has yet to be determined, MRI equaled the sensitivity of mammography in the cases studied.

Abdomen. The use of MRI for examination of the abdomen has received relatively little attention when compared with its applications in other anatomic regions. Interest has centered largely on the pancreas, lymph nodes, liver, blood vessels, and kidneys. Ehman and associates have noted the difficulties that are encountered when attempting to recognize diffuse parenchymal disease of abdominal organs where anatomic change is not involved (106). They reviewed the MR examinations of 40 patients and calculated the relative image intensity values for normal liver, spleen, pancreas, renal cortex, renal medulla, bone marrow, skeletal muscle, and fat. They developed a table of normal ranks and ranges of T1, T2, and proton spin-density for these tissues for future clinical applications.

Diseases of the pancreas have been difficult to delineate with MRI as has the entire extent of the normal organ. Stark et al have reported problems with respiratory and peristaltic motion and nonspecified variations in tissue relaxation times for a number of pancreatic conditions (107). They found that available spin-echo sequences could not reliably differentiate between inflammatory and neoplastic lesions, or, in some cases, between bowel and pancreatic tissue. Data were acquired from 50 patients with normal pancreases and 19 cases with various pancreatic lesions. CT scans were available for a portion of these patients. MRI was performed at 0.35T field strength using spin-echo sequences in all cases and inversion-recovery in selected subjects. He concluded that although MR held promise, further experience was needed before its role in the tissue diagnosis of pancreatic disease could be evaluated. Morphologic disruption of the pancreas was more easily recognized, with better visualization of vascular structures by MRI than by CT scans. This finding is consistent with a reported case of splenic artery pseudoaneurysm resulting from erosion by a pancreatic pseudocyst that Martin et al successfully detected with MRI (108). The investigators discussed the value of MRI for the diagnosis of vascular anomalies without the use of the intravenous contrast agents required by other imaging modalities.

Haaga has reviewed the limited literature on pancreatic MRI and his own experience with the technique, and has concluded that the initial enthusiasm has waned (109). He found that the sensitivity and specificity of MRI for detection and differentiation of various tumors have been disappointing. Choice of pulsing sequences for pancreatic imaging was thought to require further research so that they might be incorporated into commercially available software. Baker et al also found no particular advantage of MRI over CT in the analysis of parenchymal pancreatic disease (83).

Two studies reporting the imaging of lymph nodes appeared in 1984. Lee et al performed 23 MR examinations in 20 patients with abdominal or pelvic lymphadenopathy seen with CT in 19 and ultrasound in 1 (110). Diagnoses were histologically confirmed after excision. MRI was done on a 0.35T device using either spin-echo or inversion-recovery sequences. Most sections were transverse with some coronal and sagittal views as well. Slice thickness was 10mm. The authors reported that nodes ranging from 8mm to 15cm in diameter could be identified with MR. Abnormality could be detected on the basis of nodal enlargement and displacement of normal structures rather than tissue distinction. The authors did not consider the multiplanar capability of MR more useful than cross-sectional views. They found that MR could detect all retroperitoneal and pelvic nodes seen with CT while more clearly distinguishing them from vascular structures without contrast media. In some cases MR was not able to show small metastatic areas in normal-size nodes. The time required to survey the entire abdomen with MR was 35 to 45 minutes compared with less than 10 minutes for CT, exclusive of intravenous contrast medium injection. The long data acquisition time needed for MRI makes respiratory motion artifacts a problem. The authors foresaw a supplemental role for MRI "in selected cases where CT is indeterminate for lymphadenopathy."

Dooms and colleagues conducted a retrospective study of MRI in 60 patients who were examined for reasons other than lymphadenopathy, compared with 84 consecutive cases with pathologic nodes (111). The investigators' purposes were to define optimum spin-echo techniques for the detection of lymph nodes and then to compare MRI with CT for this task. Neck, chest, abdomen, and pelvic regions were examined using a 0.35T system performing multisection images 7mm thick. CT was found superior to MR for imaging normal lymph nodes less than 13mm in diameter. For abnormal nodes of greater dimensions, MRI and CT gave similar results, but MR was found to display lymphadenopathy best because of its "excellent soft-tissue contrast resolution." The authors recommended two specific MR pulse sequences to depict nodes: one designed to distinguish between nodes and muscle, the other to differentiate nodes from fat. They suggested that MRI holds "great promise for demonstration of lymph nodes in every part of the body."

Higgins et al reported the successful use of MRI to demonstrate intra-abdominal vascular anatomy in 1983 (112). Spin-echo protocols were developed for their 0.35T system that produced multislice images of the abdomen of 7mm thickness. Sixty-seven patients and normal subjects were studied. Because flowing blood produces very low MR signals under most circumstances, the authors found they could visualize both retroperitoneal and splanchnic arteries and veins with marked conspicuity in relation to adjacent parenchymal tissues. Both "large and medium sized" vessels could be seen without contrast medium on x-rays. It was found that the effects of abdominal lesions causing blood vessel constriction or compression could be documented. An extensive discussion of blood flow effects in MRI has been reported by Bradley and Waluch, and by Moran, Moran, and Karstaedt (31, 32).

MRI of the liver has been reviewed by Haaga (113). Predictably, there has been much research emphasis on the ability to diagnose malignant hepatic lesions by use of tissue relaxation characteristics. A study by Moss et al in 28 patients with a variety of hepatic neoplasms had found that both CT and MRI could detect tumors and metastases equally well but without histologic specificity (114). The relationship of tumors to vascular structures was better depicted with MR. Haaga has studied 30 patients with known focal lesions of the liver and 15 with diffuse disease (113). He used a 0.30T unit with various pulse sequences. It was possible to locate the area of hepatic abnormality using a set spin-echo T1 weighted technique, but distinctions between benign and malignant disease by means of pulsing variation were not possible. No differences were found between the diagnostic accuracy of CT and MRI among the patients studied. With MR sequences chosen to enhance structural features, Haaga found that the liver can be well displayed.

Two studies of MRI concerning the same three children with transfusional hemosiderosis secondary to thalassemia major have been reported. Brasch et al were able to demonstrate abnormally low levels of MR signal intensity in the liver and bone marrow of these patients, and they obtained high-intensity images from skeletal muscle and kidneys (115). They concluded that these results might be of value for the detection of biochemical pathology. The ability to assess bone marrow status in these children without risk of exposure to ionizing radiation was considered an unique advantage of MRI. Stark et al have done further work with these same patients using both in vitro MR spectroscopy and in vivo MR imaging to perform coordinated analyses of iron metabolism (116). Precise quantification of tissue iron overloads with current MRI equipment was not considered feasible. In another study of parenchymal liver pathology, Stark et al were able to distinguish cirrhosis from areas of fatty infiltration and hepatitis in a patient using MRI (117). Manifestations of portal hypertension were also seen. They noted that MRI might be used to determine the severity of chronic hepatic disease and to help physicians plan therapy without the need for biopsy.

MRI was used by Glazer and associates to prospectively identify cavernous hepatic hemanigiomata in a series of 11 patients compared with 14 cases with other focal hepatic lesions (118). Spin-echo imaging with a 0.35T system was used. Calculation of comparative T1 and T2 relaxation times did not prove useful in diagnosis. However, MR was able to detect more lesions than CT with contrast medium, ultrasound, or hepatic arteriography. MRI was found to be highly sensitive to hepatic cavernous hemanigiomata that were imaged consistently but not specifically enough to distinguish them from certain other focal lesions.

In addition to demonstrating the contrast between normal blood vessels and other abdominal organs, Ohtomo et al have successfully imaged portal vein tumor thrombosis in two cases of hepatocellular carcinoma (119). Although their experience is limited, they stated that the ability of MR to noninvasively detect structural hepatic disruption offered to have potential for further clinical applications.

Hendee and Morgan considered CT and MRI complementary and were quite optimistic concerning the overall value of MRI in examing the liver, considering it the equal of ultrasound or radionuclide scan in detecting metastases and evaluating cystic masses (16). Baker et al considered MRI the clinical equal of CT for hepatic lesions (83). Paushter et al also viewed hepatic MRI favorably with respect to conventional imaging modalities; they emphasized the need for careful selection of pulse sequences, because under inappropriate pulsing protocols lesions may appear isointense with normal liver (8).

The ability of MRI to depict abdominal vasculature has been reviewed by Higgins et al (112). Herfkens, with Higgins and others, has also reported the imaging of atherosclerotic lesions on the aortic walls (120). MRI, as a noninvasive method of evaluating abdominal aortic aneurysms, has been the subject of three recent reports. Lee et al found MRI to be an accurate method for detecting abdominal aneurysms in 20 patients with proven lesions confirmed by surgery or radiologic procedures (121). MRI was performed with a 0.35T unit using a spin-echo technique to obtain transverse and sagittal views. Coronal images were also made in five cases. The entire MR examination required less than 30 minutes to complete. Sonography or CT scanning was requested on all patients. The authors stated that management of patients with asymptomatic abdominal aortic aneurysms generally depends on lesion size. They recommended elective surgical repair for aneurysms over 6cm in diameter. Choice of a surgical approach is determined by the aneurysm's location in relation to the renal arteries and iliac arterial status. The authors concluded that MRI can provide more information than CT scans of abdominal aortic aneurysms without the need for intravenous contrast medium or ionizing radiation. Lesions were satisfactorily visualized with MR in all cases. In certain circumstances, sonography could demonstrate aneurysmal lesions, and it was considerably less costly to perform. Therefore, these investigators recommended that MRI be reserved for patients with "unsuccessful or equivocal sonographic examinations." However, they stated, MRI was more reliable than sonography for showing the relationship of an aneurysm to the renal or iliac arteries.

Amparo, with Higgins and colleagues, evaluated 14 patients with various proven aortic diseases, including eight with abdominal aneurysms, using MRI (122). A 0.35T magnet was used to perform 10 to 20 multislice transverse images of 7mm thickness. Coronal and sagittal views were obtained in some cases. Imaging time was 8.5 to 17 minutes. They reported that "the size and extent of abdominal aneurysms, the presence of thrombus or atherosclerotic debris, the relation to renal and iliac arteries, and the effect of the aneurysm on adjacent structures were readily demonstrated by MRI" in all cases. They suggested sonography as the primary screening test for the diagnosis and monitoring of abdominal aortic aneurysms because of its availability, simplicity, and low cost. However, they said, because sonography had limitations in defining luminal contents and the relation of an aneurysm to renal and iliac arteries in some patients, MRI appeared to be a reliable method for evaluating such cases. A further study of abdominal aortic aneurysms in 27 patients accomplished by the same investigators confirmed these findings (123). MRI was found to provide "all the information necessary for the surveillance and surgical correction of abdominal aortic aneurysms." Sonography was again noted to be the screening method of choice; MRI was recommended in cases where additional information is required.

Amparo, Higgins, and Hricak have also reported the results of imaging two cases of abdominal arteriovenous fistula with MRI, which correlated with the results of CT and angiography using contrast materials (124). Thirty to 45 minutes of imaging time were required for MR examination. They noted the potential utility of MRI as a preferred, noninvasive method of assessing vascular abnormalities. The same group, with Justich, has also reported the sensitivity of MRI in detecting infected aortoiliofemoral grafts in three patients (125). No other single imaging modality was considered able to provide so much information about graft infections as MRI.

Clinical experience with MR imaging of the adrenal glands has been inconclusive. Hricak reviewed the subject and found that MRI and CT scanning were regarded as equally able to depict normal and pathologic adrenal anatomy (126). CT was considered the procedure of choice for adrenal imaging. This opinion was reiterated by Davis, Hricak, and Bradley, who stated that "CT scanning probably gives more information" than MRI (127).

In a study of CT and MRI in 21 patients with various adrenal lesions and 30 normal subjects, Schultz et al found that both glands could be identified at comparable rates (128). It was somewhat easier to image the right adrenal with both modalities in some subjects because of pancreatic interference on the left. The inability of MRI to detect calcifications was considered a "serious drawback," but MRI proved better than CT in demonstrating adrenal relationships with vascular structures. Performing both imaging procedures did not increase the specificity of diagnosis in this study.

Renal imaging with MRI is facilitated by the ability to make coronal views, but respiration may produce motion artifacts, according to Paushter et al, who reviewed the status of MR for kidney disease (8). They found that the structural features and vascular relationships of normal and abnormal kidneys and their collecting system could be reliably imaged. Calcified masses produced no signal and may not be detected.

Hricak also reviewed renal imaging and reached similar conclusions (126). She specifically noted the high degree of tissue contrast resolution attainable with MRI, which may remove the need for repeated biopsies when following the progress of a lesion. In cases of chronic renal failure or non-excreting kidneys, the ability to evaluate renal disease without resorting to iodinated contrast materials was seen as a unique contribution of MRI. Tissue diagnosis in the kidney by MRI relaxation values was stated to remain elusive. The weak definition of renal calcifications, although difficult to distinguish from dense fibrous tissue, was not considered a major drawback.

Kulkarni et al performed MRI in 10 patients with benign or malignant renal masses and 10 normal persons to test MR against the pathological diagnosis of the imaged lesions (129). The investigators acknowledged intravenous urography, ultrasound, and CT as the routine diagnostic imaging modalities for renal disease. They reasoned that an evaluation of MRI against proven tissue characteristics rather than against these other imaging methods might establish its specific role in renal disease. A 0.5T system was employed with various spin-echo and inversion-recovery pulse sequence protocols to produce transverse and coronal images of 10mm to 15mm thickness. Although pathologic tissue disruptions were well visualized, their trial of calculated T1 and T2 relaxation values for tissue characterization produced equivocal results. They found that total MR imaging time per patient was comparable to CT procedures. Data acquisition time with MR was longer than CT, but computer image reconstruction time was more rapid. Overall, tumor morphology was efficiently imaged with MR, as were anatomic relationships. Use of coronal views was considered particularly helpful in this latter respect. It was possible to separate renal cortex and medulla as well as to differentiate between hemorrhagic and simple cystic fluid. The investigators did not define an exact role for MRI among other imaging techniques with respect to its tissue specificity in the diagnosis of renal masses.

These findings are similar to those of LiPuma, who reviewed his experience with renal MRI using both a 0.15T and 0.3T system (130). He considered coronal scans particularly useful for evaluating renal vasculature in the retroperitoneum and, in the case of transplants, in the pelvis. Details about his series of cases were not given, but he concluded that the ability of MR to image renal anatomy and distinguish solid from cystic masses rivaled the capacity of CT. The disadvantages of MRI that he cited included the inability to depict calcifications and a lack of standards that might guide tissue diagnosis of tumors.

MRI for the diagnosis and staging of renal and perirenal neoplasms has been studied by Hricak et al (131). Thirty-one patients were examined after CT evidence of renal cell carcinoma had been detected. MR images were read independently before a review of CT images. Diagnoses and staging based on MRI were compared with anatomic and histologic data acquired by surgery, autopsy, or biopsy. Various spin-echo and inversion-recovery sequences were used to explore their value for renal problems. A 0.35T system was used to make multiple simultaneous transverse sections of 7mm thickness in all patients. Coronal and sagittal views were done in those cases in which tumor extension required further visualization. Histological typing identified 27 renal cell carcinomas, 2 adrenal carcinomas, and 2 retroperitoneal sarcomas. Clinical diagnoses were correct in all 31 patients with MRI and in 28 patients with CT. The three cases misclassified by CT were all of extrarenal origin, mistakenly considered renal cell tumors. MRI permitted 93 percent accuracy in tumor staging among the 27 patients with renal cell carcinoma; 16 of these cases were incorrectly staged with CT. MRI was considered to have advantages in assessment of vascular patency and tumor thrombi, detection of perihilar lymph node metastases, and visualization of direct neoplastic invasion of adjacent organs and the vena caval wall.

MRI for the evaluation of renal transplants was studied by Geisinger et al (132). They found that several studies had suggested the ability of MRI to image renal corticomedullary differences (126,129,130). Geisinger proposed that loss of such differentiation may be a useful sign of transplant rejection. Nineteen renal transplant patients with 21 transplanted kidneys were evaluated using a 0.6T unit and spin-echo T1 weighted images that were selected for optimal display of corticomedullary differences. All cases were imaged with single coronal views of 10mm slice thickness. Transverse sections and multislice technique also were used in some cases. Fourteen transplants were imaged at least once in the 2 weeks following surgery. Varying patterns of followup studies were used for these patients. The remaining 7 transplants were imaged from 3 months to 7 years after surgery. Because the transplants were located in the pelvis, respiratory motion artifacts were not a problem. Scan time averaged 45 minutes, but a single multislice sequence of data acquisition required 4 to 5 minutes per plane. Geisinger et al found that MRI had limited utility in demonstrating transplant necrosis and perinephric fluid collections, especially where sonography is inconclusive. Otherwise, they gleaned little new information from MRI that was not available from conventional clinical and laboratory tests.

Renal imaging with particular attention to corticomedullary differentiation and the use of MR relaxation times for tissues diagnosis was also investigated by Leung and associates (133). Six normal subjects and 52 patients with a wide variety of kidney malformations and ailments were studied. MRI with a 0.15T magnetic field was performed. At lease six images were produced at a minimum of two anatomic levels. Slice thickness was 10mm. Diverse pulse sequences were tried with varied weighting for proton density, T1 and T2 relaxation times. All available clinical, biochemical, radiologic, histologic, and surgical findings were concurrently reviewed with MRI results to arrive at a diagnosis. Two patients were given the MR paramagnetic contrast agent (Gd)-DTPA. The authors found, in accord with the findings of others, that areas of calcification and small calcuii imaged poorly with MRI. Large calculi were identifiable. Patient respiratory motion caused blurred images in some views. MR was considered equal or superior to CT in anatomic imaging, corticomedullary differentiation without contrast agents, and demonstration of recent hemorrhage within cysts. Preferred pulse sequences for imaging various lesions were discussed, but conclusions regarding specific tissue characterization were not possible.

Williams and Hricak have reviewed the value of MRI in urology (9). While acknowledging its ability to display normal and disrupted renal anatomy, they put particular emphasis on obviating the need for iodinated contrast enhancement agents commonly used with CT scanning This feature was considered highly desirable among patients with chronic renal failure. The investigators found it to be routinely possible to do MR imaging of hydronephrosis, hydroureter, various perirenal lesions, and progressive renal parenchymal conditions and to distinguish between cystic, hemorrhagic, and solid masses. They noted that tissue diagnosis of masses and definition of parenchymal disease as well as tumor staging required further investigation, and stated that morphologic detection of adrenal lesions was easily achieved. Other retroperitoneal conditions were detected by MRI as a consequence of vascular disruption or as nonspecific space-occupying masses with greater sensitivity than with CT in some cases. The authors concluded that "for many organ sites the images produced by early generation magnetic resonance imagers already are equal in anatomical resolution to these produced by current generation CT scanners." MR images were considered superior to CT in the brain, retroperitoneum, and pelvis. Use of MR for evaluation of blood or urine flow was considered investigational.

Choyke et al have examined current approaches to imaging of urinary tract disease (134). Beyond noting the frequently cited advantages of good contrast resolution, multiplanar views, and absence of contrast agents and ionizing radiation, the authors stated that MR "in a spectrum of renal and bladder diseases indicated comparable if not superior results" when compared with CT. Smolin has drawn the same conclusions in a brief review of MRI in urology (135). Disadvantages include poor imaging of small calculi and slow imaging time.

Pelvis. Study of the pelvic region with MRI has been considered particularly successful because of the absence of interference from bone, good tissue contrast resolution, and the lack of respiratory motion (8, 9, 83). In early 1984 Hricak published a review of pelvic MRI that included a description of imaging techniques as well as an anatomical guide to MR rendition of pathologic and normal structures. She noted that the bony pelvis and marrow, vasculature, bladder, and prostate are well visualized, but only limited experience had been gained in detection of gynecologic pathology. She considered the ability of MRI to obtain direct sagittal scans of the bladder base a unique contribution because this area is not well seen with CT imaging. Later in 1984, Williams joined Hricak to review MRI in urology (9). They used a 0.35T unit with selected spin-echo and inversion-recovery sequences, chosen to produce optimum images in each clinical situation. Bladder wall thickness, irregularities, and depth of neoplasm penetration were demonstrated and local staging was considered promising. Studies of prostatic pathology were sufficiently clear that the authors suggested MRI might emerge as the modality of choice for diagnosis and staging of prostate neoplasms. Although normal penile, testicular, and inguinal canal anatomy was depicted, the investigators reported no experience with pathology in these areas. Paushter et al concurred with these findings concerning the bladder and male pelvis, but suggested that further work was needed before evaluation of endometrial carcinoma and pelvic masses in the female might be reliably diagnosed (8).

Bryan, Butler, and LiPuma summarized their cumulative experience with pelvic MRI in late 1984 (136). A 0.30T system was used; all patients examined had been previously studied with either CT or ultrasound. Numbers of cases were not given. Various T1 and T2 weighted sequences were tried for best effect in detecting lesions of interest. Transverse multislice images were made, and coronal and sagittal views were added when desired. For imaging the pelvis, MRI was thought to do best in showing the extravesical spread of tumor into perivesical fat, adjacent organs, and pelvic lymph nodes. The authors found evidence that MRI will ultimately prove superior to CT for staging of bladder tumors. They found similar results in the staging of prostate neoplasms, but they reported less success with the primary diagnosis of prostate malignancy using MRI. Rectal carcinoma, as well as its spread, could be visualized. This was viewed as a possible aid to surgery. The uterus was depicted and endometrium could be differentiated from myometrium. Distinctions between benign and malignant tumors were equivocal, based on MR tissue characteristics, but spread to adjacent pelvic structures could be documented. Ovarian masses were structurally demonstrable, but tissue type was not discernible with MR. Pelvic fluid collections were also detectable using MRI. Bryan, Butler, and LiPuma concluded that the major role of pelvic MRI will probably be the staging of known malignancies. CT was noted to understage because of its inability to detect early lymphadenopathy. It was not known if MRI might be able to detect metastatic nodes of normal size. A compensatory feature of MRI, however, was its ability to detect microscopic tumor invasion of pelvic fat, in contrast to the weakness of CT in this area. Ultrasound was expected to prevail as the principal modality for evaluation of benign pelvic conditions.

Buonocore et al performed MRI of the prostate in 10 patients with known pelvic malignancies suspected of being prostatic in origin (137). Various T1 and T2 weighted pulse sequences were used to produce 7.5mm to 10mm multislice images with a 0.6T unit. Two patients were found to have malignancies of the bladder, and 8 had prostate carcinomas. All diagnoses were confirmed by histologic examination. The investigators noted that although tumors confined to the prostate may be detected by digital examination or rectal ultrasound, use of other imaging methods has been disappointing. Thus, controversy has surrounded use of MRI for staging. In this series, information about gross involvement of periprostatic tissue and lymph nodes was obtainable, but the tissue diagnosis of intraprostatic lesions was not possible with MRI.

A study of 32 patients with prostatic pathology conducted by Poon et al produced results that conformed with Buonocore's findings (138). Using a 0.15T magnetic field, the investigators proposed to determine the optimal pulse sequence for detecting lesions of the prostate and differentiating between benign hypertrophy and carcinoma. Twenty-one normal volunteers were used for comparison. Single- and multislice techniques were used to image various planes. All MR images were interpreted by two radiologists with access to each patient's clinical data. Diagnoses were ultimately made by histologic examination of biopsy or surgical specimens. Seven patients had benign prostatic hypertrophy and 25 had malignancies. Poon noted that 2 of the patients with benign disease and 7 of those with cancer had nodular lesions, but none of the nodules could be distinguished within the gland by MRI. In the remainder of cases exhibiting diffuse enlargement, a tissue diagnosis of carcinoma was not possible on the basis of MR tissue relaxation characteristics, and normal tissue could not be differentiated. In general, these investigators were able to produce clear and accurate MR images of the prostate and its surroundings, but could not replicate the work of Hricak and Williams suggesting that prostatic tissue differences were detectable by MRI (9).

Baker et al considered MRI of the prostate "particularly promising" for evaluation of carcinoma (83). Sixteen of their 21 patients who underwent prostatic MR examination had malignancies. Overall, MRI was stated to be clinically superior to CT for imaging carcinoma and equal to CT for benign hypertrophy.

The experience with MRI in gynecology was reviewed by Thickman and his colleagues in mid-1984 (139). Images were obtained with a 0.12T unit using a single-slice T1 weighted technique to produce 13mm sections. Excellent definition of the pelvic contents was described, with the ability to distinguish solid from cystic masses and recognize invasion of surrounding structures by malignancies. Calcifications could not be seen directly. MRI was capable of delivering views with "excellent image contrast between soft tissues," which aided in evaluating the character and architecture of pelvic masses. Reliable pathologic diagnoses were not possible. MRI's advantages were listed as the absence of x-rays, no need for special preparation of the patients, and electronic control of data collection planes. Disadvantages included weak signal intensity from calcifications and cortical bone, the length of data acquisition time, and motion artifacts.

Thirty-eight patients with suspected or recurrent gynecologic malignancies were examined with MRI by Bies et al (140). The lesions were ovarian, cervical, and endomentrial carcinoma. CT and MRI scans were performed in all patients. Single-slice MR views 15mm thick were done initially; multislice methods were introduced later. Anatomic surveys were accomplished with a spin-echo protocol. Various other spin-echo and inversion-recovery sequences were used in areas suspected of pathology. Three radiologists retrospectively and independently evaluated the CT and MR images. No one

MR sequence was found to best demonstrate pathology in all patients. The investigators concluded that MRI and CT were equivalent in staging gynecologic malignancies; 11 of 16 cases (69 percent) were correctly identified. However, neither CT nor MRI could distinguish between recurrent neoplasms and radiation necrosis, inflammation, or fibrosis. The authors found that the role of both CT and MRI in the initial assessment of gynecologic malignancies had not been established, but both procedures might be efficacious as an adjunct to clinical staging.

Butler et al examined 23 women with 27 examples of pelvic pathology using MRI in all cases, ultrasound in 22, and CT in 5 (141). A 0.3T unit was used with various T1 and T2 weighted sequences to produce 15mm sections. The purpose of the study was to assess MRI's capability to distinguish between normal and abnormal tissue in the pelvis. Their series included cases of uterine, ovarian, and cervical benign and malignant neoplasms, as well as lympadenopathy and inflammatory masses. Although the number of patients with each type of lesion was small, some conclusions were suggested. Unique MR characteristics could not be identified for the disease categories studied. The investigators considered MR imaging of normal pelvic structures to approach the capabilities of CT and ultrasound, but found that the similar appearance of pathologic processes on CT and sonograms did not ensure the same appearance on MRI. Ovarian cystadenomas were found particularly difficult to image consistantly. Thus, an overlap of MR signal characteristics occurred between various pathologic tissues as well as within the same types of entities.

MRI, as a useful modality for obstetric diagnosis, is still in a preliminary stage. Weinreb reviewed the topic in early 1985 and found that few case studies existed (142). Five patients with abnormal pregnancies involving three fetal anomalies, a hydatid mole, and an unidentified pelvic mass concurrent with an early pregnancy were studied. All had ultrasound before their selection for MRI. Weinreb was able to display fetal and maternal structures satisfactorily with MRI, but noted degradation due to fetal motion in some instances. He foresaw a possible role for MRI when medical or surgical conditions complicate pregnancy and x-ray procedures ordinarily might be required. Other indications were thought to include cases in which ultrasound evaluation was difficult or produced equivocal results.

Thickman et al used MRI to examine three fetuses in utero (143). They were previously known to have severe cerebral abnormalities, on the basis of sonographic data as well as other clinical information. Diagnostically useful MR images were obtained with a 0.12T field using single-slice T1 weighted technique, 22mm thickness, and an imaging time of 2.5 minutes. Motion artifacts were not found. Future application of MRI in obstetric practice was suggested.

Eleven patients in the last trimester of pregnancy with sonographic evidence of abnormal fetal growth or anomaly were given MRI examinations by McCarthy et al (144). Their purpose was to study maternal pelvic structures during pregnancy. Similar MR views of five normal subjects were employed for comparison. Transverse and sagittal MR images were acquired with a multislice spin-echo technique using a 0.35T system. This study found that MRI could accurately define the maternal pelvis without significant motion artifacts. Specifically, the authors concluded that "MR offers superb delineation of the internal changes of the cervix during pregnancy." Because cervical tissue strata could be visualized, they suggested that its structural and physiologic status during effacement could be assessed more exactly with MRI than with digital or sonographic examination. In addition, they expressed the opinion that sagittal images of the maternal spine and direct detection of venous stasis were of potential diagnostic value. They noted that MRI holds promise as an obstetrical imaging modality.

McCarthy and co-workers also published a companion report on obstetrical MRI for evaluation of fetal anatomy (145). Nine patients in the third trimester with sonographic evidence of high risk were studied. Various pulsing protocols and imaging planes were used to determine optimum conditions for fetal imaging, and the results were compared with high-resolution sonographic images. They found that normal fetal anatomy was best depicted with sagittal (maternal) views. They did not consider fetal motion to be a problem, but suggested that younger fetuses or patients with polyhydramnios might be more mobile. Placental size, location, and umbilical cord insertion were seen in all patients. Overall, the fetal cardiovascular, pulmonary, and central nervous systems were readily imaged. The study concluded that sonography remains the procedure of choice for fetal imaging, but MRI shows promise as a complementary noninvasive modality that permits in vivo evaluation of fetal tissues and fluids within the amnion.

Stark, with the same group of investigators, also used MRI to evaluate intrauterine fetal growth retardation (146). In studying 11 high-risk fetuses in the third trimester, the authors found that decreased fetal subcutaneous fat stores correlated with malnourishment--a presumed cause of intrauterine growth retardation. They suggested that small, well-nourished fetuses might be separated from malnourished ones with MRI. Sonography was noted to detect fetal size variation, not fat stores, and thus was less predictive of malnourishment.

Musculoskeletal system. The use of MRI to diagnose musculoskeletal disease has been reviewed by Scott, Rosenthal and Brady (147). They commented that, of the predominant constituents of the extremities, only bone is well defined by conventional radiographic methods. They noted that MRI rendered superior soft-tissue and bone marrow contrast, which tended to compensate for its "slightly poorer" spatial resolution when compared with CT. Specifically, T1 and T2 tissue relaxation times were found to differ sufficiently among bone, ligaments, and tendons and tumors, muscle, and fat to permit adjustment of pulse sequences for optimum tissue discrimination. Blood vessels with rapid flow rates generally produce weak signals distinguishing them from their surroundings. The reviewers suggested that tissue diagnosis of particular bone and soft-tissue lesions by means of MR appearance was not yet possible. Structural disruptions due to malignant and nonmalignant processes were considered demonstrable. Primary and invasive tumors of bone, replacement of marrow by neoplasia or other tissue, and various soft-tissue lesions could usually be visualized. The investigators advised further research into tissue-specific MR characterization of musculoskeletal diseases.

Baker et al reported their experience with MRI in the musculoskeletal disorders of 105 consecutive patients (83). Tumors, infections, and trauma were well represented. They found that "in all cases, MRI depicted the extent of the lesion and its involvement of and distinction from normal tissue better then CT." When metal prostheses were present, CT was often obscured by artifacts, whereas MRI "was only minimally affected." Injuries of tendons, ligaments, and muscle were noninvasively displayed "with a clarity heretofore not possible." Vasculature and neural structures that may be damaged in conjunction with more obvious bony lesions could be usefully visualized with particular clinical value. The detection of infection was generally associated with prosthetic joints or immunosuppressed patients. The process could be identified earlier, and its extent better judged, with MRI than with CT.

Noting that direct visualization of the internal structures of the knee has not been possible without invasive procedures or use of contrast magnets, Li et al have proposed MRI for this purpose (148). They examined 11 normal subjects with a 0.15T system using spin-echo multislice technique and 10mm section thickness. They varied the imaging planes and subject position to facilitate visualization of the particular structure under study. They found it possible to accurately display "menisci, cruciate ligaments, articular cartilage, cortical and cancellous bone, muscles, tendons, subcutaneous and intraarticular fat, and blood vessels" without the use of contrast materials. Because imaging planes could be varied without stressing or moving the knee, MRI was considered particularly apt for patients with painful conditions. Cortical bone, ligaments, and menisci were best seen when contrasted with surrounding soft tissues. Mineralization of bone or periosteum was not easily assessed. Li et al concluded that although the specific uses of MRI in the knee remained to be defined, MRI's ability to visualize the menisci and cruciate ligaments without the use of contrast agents is unique among imaging modalities.

The use of MRI in examining injured knee ligaments was studied by Turner et al (149). Eleven acutely injured knees and 13 normal knees were imaged with a 0.5T unit using spin-echo sequences supplied by the manufacturer. With the exception of two patients, all images were done with single-section methods and 15mm thickness. MRI in the last two patients in this series was performed with multislice technique and 10mm thickness. Ten injured patients were examined within 72 hours of trauma, one was done a week after injury. Diagnoses were confirmed by arthroscopy or open surgery. An MRI diagnosis of ligamentous injury was based on the judgment of two observers using criteria developed early in the study. Overall, 11 of 15 torn knee ligaments were detected with MRI, while 1 of 81 normal ligaments was incorrectly called abnormal. Turner et al found that ligaments emit very low intensity MR signals and can be seen only as a result of their contrast with adjacent soft tissue and fluid. They predicted promise for further clinical utility of MRI but suggested larger prospective studies of larger series.

Zimmer et al reviewed the use of MRI in bone and soft tissue tumors and presented a case of aneurysmal bone cyst (150). The authors stated that several investigators had reported the ability of MRI to depict primary and metastatic bone tumors accurately. The authors expressed the opinion that the detection of masses, appreciation of their extent, and information on their structure may be better acquired with MRI than with CT. They cited diagnosis of an aneurysmal bone cyst of the femur as a case in point. MRI provided preoperative data that was of clinical value. The relationship of lesion to epiphyseal plate and its boundary with the medullary canal and soft tissues were considered to be more sharply defined than with CT. Coronal and sagittal images were particularly useful. Zimmer et al also concluded that MRI is the procedure of choice "in the evaluation of recurrent tumor after the insertion of metallic prostheses or fixation devices." Tissue diagnosis of specific lesions based on T1 and T2 values was not considered fully evaluated.

Zimmer et al performed MRI examinations in 52 patients with skeletal lesions suspected of being bone tumors (151); 32 had primary bone neoplasms (25 malignant, 7 benign), 15 had metastatic lesions, 4 had osteomyelitis, and 1 had an aneurysm of the internal iliac artery. Surgical confirmation was possible in 49 of these 52 cases. Conventional radiographs were available for all patients; 31 had radionuclide bone scans and 45 had CT imaging. Among the group with CT scans, MRI was superior to CT in demonstrating the extent of tumor in marrow in 33 percent of the cases, was equal to CT in 64 percent, and was inferior to CT in 2 percent. Cross-sectional MR views were obtained in all patients, with sagittal and coronal planes also imaged in some cases. A 0.15T system was used with various multisection pulse sequences to produce 10mm slices. Spin-echo sequences with a long repeat time were found to be most useful in demonstrating bone tumors. The authors recommended MRI in at least two planes as the next diagnostic examination to be performed after discovery of a possibly malignant bone lesion on plain radiographs. They suggested CT of the chest to search for metastases. They estimated that MR imaging of bone tumors required about 30 minutes to complete.

Idiopathic avascular necrosis of the femoral head (Legg-Calve-Perthes disease) in 14 children was evaluated with MRI by Scoles and associates (152). These patients had lesions of varying duration. The investigators used clinical data, conventional radiographs, and bone scans, when available, in addition to MRI for assessment and staging of their condition. Imaging was done with a 0.3T unit employing both spin-echo and inversion-recovery pulse sequences to produce transverse and coronal views. In affected hips, femoral areas of infarction produced weakened MR signals. Image resolution was improved with the use of small RF detection coils. Among nine patients who had conventional bone scans, MRI proved to be of equal sensitivity to infarction. Scoles et al found that MRI was capable of forming accurate images of this disease, which were of clinical value without contrast agents. This work is described as preliminary with problems of "resolution and image reconstruction" remaining to be solved before MRI reaches its full potential. The investigators concluded that standard radiographs cannot be eliminated yet in the clinical diagnosis of this disease. A further refinement of technique has been reported by Matthaei et al, who employed experimental chemical-shift-selective MRI to produce separate "water" and "fat" MR images in a case of femoral avascular necrosis (153). Additional information about the lesion was produced when compared with conventional MRI methods.

Totty et al used MRI to evaluate 20 patients with ischemic necrosis of the femoral head, compared with 38 normal femurs (154). Patients ranged in age from 22 to 73, and were either at risk, suspected, or known to have ischemic femoral head lesions. Images were acquired on a 0.35T system employing a variety of spin-echo and inversion-recovery pulsing methods. The results of MRI were compared with conventional radiographs in 14 patients and with bone scintigraphy in 12. Nine patients had both procedures. In reviewing ischemic necrosis of the femoral head, Totty proposed that early diagnosis was important because the lesion is known to be associated with a variety of conditions for which rapid institution of therapy might avoid major structural changes in the hip joint. Radiographs were stated to depict bone mineral density, whereas scintigrams depict deposition of a radioactive tracer by blood flow. Scintigraphy was found to identify ischemic femoral areas an average of 14 months before radiographic changes can be seen. MRI derives its imaging signal from the fat and hematopoietic cells of the marrow. In 15 of 20 patients, MRI depicted abnormalities of the femoral head. It showed abnormality in all cases that were abnormal by radiographic or scintigraphic findings, or both. MRI was positive in one hip with a normal radiograph, and in five hips with normal scintigrams and abnormal radiographs. The authors concluded that ischemic necrosis of the femoral head can be identified, but is not specifically diagnosed, with MRI, because any lesion that replaces the fat of bone marrow will image with reduced signal intensity. They suggested that patterns of disease progression can be correlated with clinical information to determine the prognostic utility of MRI in such patients.

Twenty-nine patients were examined for peripheral vascular disease secondary to atherosclerosis by Reynolds et al (155). They compared the ability of MRI and xeroangiography to define the patency of the popliteal artery. Conventional contrast arteriography had been previously performed in all cases. MR images were obtained with a 0.15T system, which produced four consecutive single-slice views above and below the knee. Patent vessels produced no signal on MRI, whereas thrombi and clots within occluded arteries produced MR emissions. The level of contrast between patent and occluded vessels was low, making interpretation difficult. Overall, 39 MRI scans (86 percent) correctly revealed the state of the popliteal artery in 46 legs compared with an arteriogram. There were 5 false positives among 41 patent vessels, 1 false negative among 5 occluded vessels, and 1 technically unsatisfactory examination. Xeroangiography produced statistically similar results. In view of the fact that contrast agents and radiation are not required, the investigators noted that MRI was promising for evaluating peripheral vascular disease, but said that further investigation appears necessary.

Safety and Efficacy

To date, there has been no evidence that MR imaging causes biological harm. Possible biological risks have been classified into three categories: "the effects of high-intensity static magnetic fields, the minute electrical potentials and currents induced by changing magnetic fields or by blood flow in a static field, and possible heating from the radio frequency pulse" (3). Harm might be caused by the torque that strong magnetic fields can produce on biologic materials such as sickled erythrocytes, retinal rods, and possible changes in the shape of enzymes leading to changes in their activity. Nerve conduction velocities might be affected and movement through a magnetic field might induce voltages and currents that affect other biologic electrophysiologic phenomena.

Transient cardiac T-wave changes of unknown significance have been noted to occur during exposure to strong magnetic fields. The Food and Drug Administration (FDA) suggested guidelines for MRI trials which set electromagnetic exposure risk levels that have been used to determine when a study might involve a "significant risk" to the subject with respect to static, changing, or RF magnetic fields. For static fields, a 2.0T limit for whole or partial body exposure has been set; for changing fields, the limit is 3.0T per second. For whole-body RF absorption, a guideline of 0.4 watts per kilogram has been established (156). Hendee and Morgan stated that two contraindications to MRI currently exist: pregnancy and cardiac pacemakers (3). An analysis of known biologic thresholds based on in vivo studies of MR effects has been published by Budinger (11). Although no discernable hazards exist at current levels of clinical MRI exposure, he suggested that no hypotheses have been drawn concerning what future effects might be expected. He also stated that a prospective study with a sufficient sample size of exposed individuals to reveal such effects was problematic.

Davis et al studied the heating effects of RF fields and changing magnetic fields in vitro on various surgical clips and hip prostheses (12). No significant heating was found at field strength levels proposed for clinical MRI.

In 1984, Saunders and Smith, of the National Radiological Protection Board in England, found no occurrence of adverse effects attributable to MRI among 2,000 clinical examinations performed (157). They did suggest, as a matter of prudence, that pregnant women in the first trimester, persons with cardiac pacemakers, and persons with intracranial metallic clips be excluded from MRI procedures. Large metallic implants, such as prostheses, were not considered an absolute contraindication, but it was recommended that MR exposure be stopped if discomfort due to heating was experienced. Pavlick et al noted the multiplicity of available cardiac pacemakers and the uncertainty of their susceptibility to MRI-induced malfunction (158). They proposed 10 Gauss as an "acceptable limit for controlling access to an NMR environment" for pacemaker patients.

New and his colleagues reviewed the possible risks due to metallic implants in MRI patients (159). They found a predictable relationship between the alloy composition of metallic clips and their deflection by magnetic fields, which poses a possible hazard, particularly in the case of vascular clips. Foreseeing a time when MRI will be in widespread use, they suggested that future metallic implant materials have low or no ferromagnetic properties.

Mechlin et al reported their experience in six postoperative patients with extensive abdominal or pelvic metal surgical clips and in four with hip prostheses (13). Comparable CT and MR scans were performed. In four of the patients with clips and in all with hip prostheses, significant streak artifacts were encountered with CT that impeded interpretation of the images. MRI produced scans that were free of artifacts, although a "focal loss of signal without distortion" was noted in the hip patients. "Most" clips used in the authors' institution were said to be of tantalum, a nonmagnetic material. MRI was found to be particularly useful in postoperative patients for whom metallic implants limit the utility of CT scans.

Soulen, Budinger, and Higgins have performed in vitro studies of prosthetic heart valves currently found in patients to determine their susceptibility to adverse effects from MRI exposure (160). Nine different valves were studied in MRI devices with fields of .035T to 2.35T. They concluded that patients with current prosthetic heart valves can be safely imaged in MR units of current design.

Wolff, with others, has updated his previous work with cell cultures exposed to MRI by repeating these experiments using a 2.35T magnet over extended periods (161). Human lymphocytes and Chinese hamster ovary cells were exposed for 12.5 hours to the MRI device, with no resulting increase in chromosome or sister chromatid exchanges. They concluded that "long-term exposure to MR imaging conditions far exceeding those to be found in the clinical situation does not cause cytogenic damage."

Strong magnetic fringe fields, principally generated by resistive and superconductive MR magnets, have been of concern for safety reasons and for their possible role in image distortion (3). Nearby objects made of magnetic materials may become hazardous missiles if drawn into the static field of an MRI unit. Large magnetizable objects such as elevators, vehicles, or steel beams may cause distortion of magnetic field uniformity, leading to image degradation (3,15). The magnitude of these effects may be determined by the design characteristic of the specific device being used. Roth et al have studied the effects of patient-monitoring and life-support equipment on the process of MR imaging (15). Twenty patients with a variety of devices that monitored their vital functions had 20 pairs of MR scans performed, which covered all anatomic regions with and without the monitors in place. Three blinded observers read the images to discern differences between the pairs with respect to image degradation. A monitoring system was developed using commercially available products that permitted observation of blood pressure, heart rate, ECG, and chest wall motion during MRI without affecting image quality. Patients requiring intravenous medication and tracheal intubation have also been successfully scanned.

Because MRI can be a lengthy procedure conducted in a very confined space, patient claustrophobia, anxiety, and acceptance have been of interest. Weinreb et al discussed their experience with these problems among 450 patients (14). They instituted a patient education program and took other measures to improve the imaging environment and communication during MR examinations. Only 1 of 450 cases could not be imaged, but light sedation was employed in some situations. Weinreb et al described carefully selected nonferromagnetic equipment and emergency procedures that minimized potential hazards peculiar to strong magnetic fields. They also took an informal survey to assess patient impressions of MRI. The patients most frequently remarked favorably on the absence of intravenous or oral contrast materials and ionizing radiation, which was "of prime importance to many patients." They commented negatively on boredom and the length of the procedure, as well as on feelings of confinement.

An extensive compilation of known data concerning the potential health hazards and safety considerations of MRI was edited by Persson and issued in 1984 (162). No general health hazards were identified in the range of electromagnetic parameters employed for in vivo clinical MRI, but the bases for possible biophysical effects were discussed.

Two comprehensive reviews of MRI have now been published. Steinberg, Kaiser, and Cohen prepared a "clinical, industrial, and policy analysis" for the Congressional Office of Technology Assessment in September 1984 (23). DiMonda wrote a Guideline Report on MRI for the Hospital Technology Series of the American Hospital Association in January 1985 (17).

The work of Steinberg, Kaiser, and Cohen reflects the clinical status of MRI as of the first quarter of 1984. They concluded that continuing research will be required until the potential of MRI is determined. It was "thought to be capable of providing not only anatomic information comparable or superior to that obtainable with other imaging techniques, but also chemical and metabolic information that could yield noninvasive insights into tissue histology and function." Because MRI is free of demonstrated hazards and can produce high-contrast images without potentially toxic contrast agents, the authors suggested that an important clinical role for this technology was assured "even if it proved to be no more efficacious than x-ray CT scanning." The excellent spatial resolution and contrast resolution of MRI as well as the absence of bone artifact were also cited as advantages. Cost, exclusion of patients with metallic implants, insensitivity to bone and calcifications, and long data acquisition times leading to motion artifacts were listed as disadvantages. Clinical applications were perceived to be constantly evolving. In most studies, patients with known pathology had been imaged, which predictably biased the estimates of MRI's sensitivity and specificity in detecting disease. Steinberg, Kaiser, and Cohen also remarked that optimal pulse sequences were being sought in order to image specific medical problems reliably. They expressed the view that the results of this search would be built into future commercial MRI software to become algorithms for screening procedures. The use of fixed sets of multiple sequences might further increase the time required to perform MRI examinations. The investigators considered the uncertainty between selection and use of multiple pulse sequences and the making of a clinical decision that pathology had not been overlooked to be potential sources of controversy. They noted that an additional economic impact would stem from the absence of risk from repeated scans for monitoring patients' progress. They considered MRI of the brain and CNS to be most efficacious, with imaging of the heart and pelvis termed "particularly promising."

DiMonda employed published clinical data available through the end of the third quarter of 1984 to prepare his evaluation of MRI (17). He included additional data from interviews with researchers and clinicians extending into the fourth quarter of the year. He presented an informative analysis of the debate surrounding choice of an optimal magnetic-field strength for clinical MR proton imaging. DiMonda suggested that the resolving power of an image is the characteristic that permits "confident differentiation of a feature from the surrounding background." He stated that this is a function of signal-to-noise ratio, contrast-to-noise ratio, and spatial resolution. He discussed the many interactions of MR parameters, including field strength, that ultimately contribute to resolving power. DiMonda concluded that system refinement, not simply magnet size, was the major issue in the evolution of MRI. Specifically, he expressed the opinion that developments in coil and electronics technology to obtain the highest quality images in the least time were important and will ultimately be a measure of the individual manufacturer's commitment to technical research and development. He concluded that variations in field strength among commercially available MRI units for clinical proton imaging were of minor importance as determinants of productivity or image quality.

These findings are in accord with the earlier findings of Crooks et al (7). Higher field strengths might be required for MR spectroscopy, but DiMonda expressed the view that these applications were acknowledged to be investigational and that optimum magnet size has not yet been determined.

An analysis of methodologies to project the future utilization of MRI was a significant feature of DiMonda's work. He remarked that some evaluations have leaned heavily on inpatient data despite increasing evidence that most MRI will probably be performed as an outpatient procedure. In response to these shortcomings, the American Hospital Association (AHA) assembled a panel of experts with MRI experience who reviewed 321 ICD-9-CM diagnostic categories. DiMonda arrived at a "conservative model" for utilization that predicted 1.8 million scans annually. When these data were compared with similar projections for CT use, it was found that MRI would replace 34 percent of CT overall. By body systems, it was projected that MRI would replace 94 percent of CT for nervous system disease, 75 percent for circulatory system disease, and 30 percent for neoplastic disease. These projections represent a net increase of about 1.3 million new scanning procedures per year; they are based on the projected number of MRI scans not balanced by corresponding diminutions in CT utilization. More than 200,000 MRI procedures projected for muculoskeletal and connective tissue applications contributed significantly to this net annual increase, because CT applications for such purposes were noted to be minimal, with no replacement foreseen. The author concluded that MRI's role as a useful clinical tool had been established, but major issues with respect to the financial impact of providing MRI services remained to be investigated. Control over a large patient referral base was considered crucial. The author suggested that radiologists have 18 months of training to "fully understand the technology and be able to use it most effectively although some diagnostic skills can be learned in three months." Much of this training reflects the need to understand the principles that underlie the choice of pulse sequences and the need to acquire the ability to interpret images composed of hitherto unavailable data.

Clinical applications of MRI were reviewed by Hendee and Morgan in late 1984 (16). They concluded that all major organ systems were amenable to MR imaging. Superior contrast resolution was obtainable in the brain while bone and motion artifacts were absent in scans of the abdomen and pelvis. They considered use of MRI for imaging the heart and great vessels to be developmental, as was MR spectroscopy. They stated that diffusion of MRI was largely dependent on economic factors. Although the authors questioned whether enough data are available to recommend MR installation in most hospitals, they suggested that institutions considering the acquisition of an additional CT unit should consider an MRI system in its place. They did not specifically discuss outpatient applications.

Baker et al expressed uncertainty concerning the "true role of MRI in relationship to other methods of diagnostic imaging," but noted that in the first 1,000 consecutive MRI patients at the Mayo Clinic the device "was found equal to or superior to other imaging techniques in most cases" (83). Organs or anatomic areas subject to respiratory or cardiovascular motion, small lesions requiring "exquisite spatial resolution for detection, fresh blood, and calcifications" were found difficult to depict. Overall, MRI images were evaluated post hoc and found superior to CT for musculoskeletal lesions, including tumors, infections, and soft-tissue trauma; prostatic carcinoma; lesions in children such as mediastinal widening or suspected lymphoma, thymoma, or thoracic vascular abnormalities; and certain cardiac diseases. MRI images were considered equal to CT for many chest lesions, renal lesions, hepatic lesions, and prostatic hypertrophy. MRI was considered inferior to CT in depicting pancreatic lesions, thymoma, parathyroid adenoma, and small pulmonary nodules. In order to evaluate MRI for imaging the head, neck, and CNS, the investigators developed a classification system with six major categories of conditions: tumors; vascular disease; inflammatory disease; developmental conditions; traumatic, orbital, or metabolic conditions; and neurologic syndromes. Among 30 of 36 diagnostic-pathologic subdivisions of these six groups, MRI was found to be equal or superior to CT or myelography. The inability to detect calcifications or to distinguish between fresh and old bleeding, and the inferior spatial resolution of small lesions were frequently cited drawbacks of MRI. The absence of ionizing radiation was noted to be a particular advantage of pediatric MRI. The authors concluded that "even at this early state, however, MRI is obviously a very powerful clinical diagnostic tool that in many applications is more sensitive than CT and myelography." They suggested the use of MRI as a patient-screening technique.

In the absence of controlled clinical trials, appraisal of MRI's capabilities and utility has relied heavily on published case studies, which Di Chiro has characterized as "an avalanche of articles that are limited in material and scope" (163). The interpretation of MR signal variations due to subclinical changes in tissue composition and the diagnostic utility of T1 and T2 relaxation times were recognized as areas requiring additional research. The current status of MRI in clinical practice was not discussed.

A number of editorial commentaries on the diffusion and acceptance of MRI now have appeared. In the Western Journal of Medicine, Brown and Gerber expressed the view that the clinical use of MRI had been "validated by late 1983 as a result of clinical trials accomplished over the preceding three years" (164). They perceived the current applications of MRI as suitable for the noninvasive anatomic depiction of pathologic processes and recognized the potential value of MRI for the visualization of metabolic and pathophysiologic cellular processes. In January 1984 a Lancet editorial stated that MRI had proved sensitive to a variety of neurologic lesions but that its role in the remainder of the body had been found to be "less obvious" (22). Most existing MRI devices were considered to be research prototypes awaiting stabilization and commercial development.

In a 1984 volume of Radiology, Murphy compared MRI with CT and found that "a new technology that can immediately equal CT should be viewed as impressive" (165).

He considered MRI superior to CT for anatomical imaging of the heart and great vessels, posterior fossa, and cervical spine. Murphy also argued that MRI should be compared with other procedures as well, many of them invasive, lest comparison with CT be thought most important. He concluded that MRI costs would ultimately be close to those for CT, and more beneficial diagnostic information would ultimately be obtainable than is now the case with conventional modalities. He enthusiastically suggested that the public, the government, and the medical profession should actively support MRI technology.

Vannier, in late 1984, saw MRI as competing favorably with CT and ultrasound (5). He considered MRI's clinical use for evaluation of CNS disorders to be most advanced. In addition, he regarded as useful the imaging of solid and vascular mediastinal masses, aortic aneurysms, and dissections, in addition to sagittal and coronal images of the retroperitoneum and pelvis. Vannier advised prudent use of MRI in "areas where its efficacy has been established," but he proposed no methodology for evaluating efficacy in this context.

Selzer reviewed the clinical potential of MRI in December 1984 (166). He was optimistic concerning the future of MRI, but considered its use for detecting white-matter disease of the brain "the only instance in which MRI provides information far excelling any other modality." Selzer suggested that "the only appropriate place for such scanners at the present time is in major medical centers where ongoing research and clinical trials can determine their optimum use."

Schroeder published a commentary on MRI in April 1985 (19). He found too little information available to assess its relative clinical advantages over other imaging modalities with respect to its diagnostic sensitivity and specificity. He foresaw market conditions rather than clinical trials per se as the ultimate determinants of the extent to which MRI can succeed among similar technologies.

Because the basis of MR images is linked to the physical and chemical characteristics of a tissue, the acquisition and interpretation of images that provide optimal clinical benefits will be the subject of future research. In general, interest has centered on technical improvements in tissue-contrast rendition, spatial resolution, and reduction of imaging time (26-29). These qualities of MRI have been of principal concern in the depiction of normal and disrupted anatomy of body structures. The reproducibility of imaging techniques for consistent detection of tissue differences will certainly continue to be studied (81,167). Spatial resolution has been improved through the development of surface coils to improve signal-to-noise ratio as well as through the work with software modifications to improve selection of imaging planes and image reconstruction techniques (168-169). Gated MR images of the heart and other organs have been made in an effort to overcome the distortions of motion artifacts. Various gating methods have been reported involving the triggering of MR pulse sequences in synchrony with the R-R wave interval of an ECG, plethsymography, or a laser-Doppler system (170-172). Higgins et al have published their experience with 172 patients who had cardiac MR imaging (173). Of this number, 31 were normal subjects and the remainder had a wide variety of heart lesions. Cardiac-gated pulsing was employed in all but three patients. The investigators found gating to be a satisfactory method of data acquisition "for aiding the diagnosis of pericardial diseases (except pericardial effusion), and for the evaluation of paracardiac and cardiac masses." They found gating to be inferior to echocardiography for the "evaluation of cardiac valves and for the functional assessment of the ventricles." In general, the authors found gating to be effective in accurately depicting a variety of anatomic cardiac abnormalities, but they used three different gating methods and the number of patients in each diagnostic category was small.

Pharmaceutical contrast-enhancing agents for MRI are being sought as a means to selectively identify pathologic processes or shorten imaging times. After a review of this topic, Brasch concluded that the use of MR contrast agents is promising but their ultimate role in clinical imaging "is now uncertain" (174).

Finally, the specificity of MR relaxation times for the tissue diagnosis of lesions compared with normal structures will continue to be investigated (21). At this time little success has been reported with such distinctions.

DISCUSSION

The evaluation of an imaging modality remains an area of considerable controversy. Although one might wish for scientifically sound data on which to base conclusions about the clinical utility or patient benefits attributable to one or another diagnostic imaging method, there is a paucity of such information. In 1978, when CT scanning was in its fifth year and 1,000 units were in operation, Fineberg editorialized on its evaluation in the AJR (24). He discussed the difficulty of reconciling remote health outcomes with the ability of a new device to better depict anatomy and pathology, and he analyzed an array of possible assessment strategies. He concluded that the issues were complex and that short, definitive answers were elusive. He found that "empirical evidence can only support particular levels of efficacy for particular groups of patients at particular costs." Various methodologic models for the measurement of CT efficacy have been proposed, but they rely heavily on process observations and remain quite limited in scope (175, 176). The differences in diagnostic accuracy among competing imaging modalities are difficult to interpret in terms of ultimate therapeutic benefit.

These methologic problems were most recently addressed by Gelfand and Ott in 1985. They remarked on the continued shortcomings of studies that compare the diagnostic efficacy of imaging techniques (177), noting that evaluative techniques applied to diagnostic imaging are often derived from the fields of laboratory testing or drug studies and may be inapplicable. They suggested that further work on improved research design and statistical procedures was needed. If consistent information were available on the optimum clinical efficiency and efficacy of comparable imaging procedures, which is not the case at present, they said, then the ideal of a comprehensive diagnostic algorithm might be approached.

The literature of proton MRI is largely a series of impressions, albeit knowledgeable, concerning its ability to depict normal or disrupted anatomic structure. Studies that have attempted to correlate specific tissue relaxation time patterns with specific pathologic diagnoses have produced inconclusive results. Thus, the basis for evaluating MRI must be as a structural representation rather than as a "noninvasive biopsy." In this context, much of MRI's value stems from the visual information an image provides. This information theoretically enables a clinician to efficiently achieve therapeutically benefical results after relating structural features to the signs and symptoms of a patient. The results achieved may range from a definitive diagnosis, based on observation of a pathognomonic lesion, to measurable variations in structural dimensions that would assist in planning surgery. Most published MRI studies have emphasized the comparative depiction of known lesions among limited groups of patients previously imaged with some combination of CT, sonography, or radiographs. Thus, the relative conspicuity of tissue visualization has generally been evaluated post hoc using conventional imaging modalities as the standard of comparison. A few studies have employed independent readers unaware of non-MRI data. Concealment of the modality at hand was, of course, not possible, and the initial selection of patients accorded MRI has been quite biased even among prospective studies.

Given the fact that MRI does not involve use of ionizing radiation or intravenous contrast agents, its performance in relation to CT becomes difficult to assess. The risks of x-ray exposure are epidemiologically quantifiable, as the work of Feig has demonstrated (178). Iodinated contrast agents frequently used with CT carry a risk for those with renal impairment or sensitivity to the material itself. Brasch, Boyd, and Gooding considered the risks of both radiation and contrast agents in CT scanning of children (179). Although the risks were found to be low, they nevertheless exist and must be balanced against expected benefits. By late 1984, Gooding and colleagues found CT a less desirable repetitive diagnostic study than MRI in children with cystic fibrosis by reason of the cumulative radiation dose that CT entails (180).

Cost, as a factor in the acceptance and diffusion of MRI, has attracted keen interest, particularly in the light of experience with CT scanning and certificate-of-need statutes (17,18,23). Hillman et al analyzed the components of a decision to acquire an MRI unit or to defer its purchase (181). They found that most MRI procedures are being performed on ambulatory outpatients, a group that is not affected by DRG prospective payment arrangements. This conclusion is amply supported by the clinical literature, where scant attention has been focused on MRI in hospitalized patients with acute illnesses. As already noted, attempts at cost-benefit analyses of both CT and MRI have been thwarted by a lack of health outcome data and by the multiplicity of uses for a diagnostic image.

No universal standard has been developed that might be employed to measure the achievements and current status of MRI. At the level of anatomic display, the technical attributes that distinguish this modality are its ability to depict soft-tissue structures with marked inherent contrast. Although cortical bone and calcifications are not well visualized per se, this aspect of MRI has been of assistance in examining the contents of bony structures without the artifacts commonly encountered with CT. Lesions of bone marrow, the posterior fossa, and primary or metastatic bone tumors, as well as disorders of the vertebrae and intravertebral discs, can be displayed because of this characteristic. Flowing blood produces a weak MRI signal under usual circumstances and serves to contrast vascular structures with other organs and tissues. Surgeons and oncologists often seek such information. Significant applications of this feature of MRI have been reported in the display of thoracic and abdominal aortic aneurysms and dissections; in the examination of the mediastinum, retroperitoneum, and pelvis; and in the study of various musculoskeletal disorders.

The issue here is not the ability of MRI to detect specific diseases, but rather the potential to depict neoplastic, metabolic, or mechanical disruptions of major vasculature when used by knowledgeable practitioners. Distinction of parenchymal tissue variations in organ systems as well as neoplasms has received the major share of scientific attention. Foremost among these have been the central nervous system, pancreas, kidneys, liver and prostate. Because MRI will differentially image gray and white matter as well as space-occupying lesions, anatomic disruption, demyelinating lesions, and some inflammatory processes, it has been considered a mainstay of neuroradiology. It has enabled practitioners to examine the cervical cord in conjunction with the brainstem, cerebellum, and hemispheres as a continuous unit without use of contrast agents. The literature reflects the fact that MRI has found its most frequent applications for examination of the brain and spinal cord. A degree of controversy exists with respect to its use for diagnosing herniated vertebral discs and its sensitivity to cerebral tissue characteristics that are not always histologically demonstrable. These issues of sensitivity and specificity are in large part dependent on whether MRI is considered to be a noninvasive screening modality or a definitive diagnostic procedure in relation to the case being studied.

There is a consensus that the extended image acquisition time required by MRI leads to problems with motion artifacts. Although respiratory and cardiac gating have been employed for anatomic and functional studies of the heart and other organs, it remains a research tool at this time. A similar condition exists with surface coil technology. Current MRI devices are limited in spatial resolution by slice thickness and volume-averaging effects. Contrast resolution superiority has frequently been cited as a compensatory factor that results in improved conspicuity. Surface coils remain investigational, although their use has potential for improved MR spatial resolution. Pharmaceutical contrast-enhancing agents constitute another investigational effort to shorten imaging time and improve diagnostic accuracy (174). To date, no MRI surface coil or contrast material has been approved for commercial distrbution by the FDA.

The measurement of tissue T1 and T2 relaxation parameters as a method of biochemical tissue diagnosis to identify malignancy or other lesions has not been reliably demonstrated at this time, nor has MR spectroscopy. Neither can be supported as mature clinical procedures by the existing literature.

There are no data available to indicate that MRI devices operated within their labeled imaging parameters are hazardous in routine clinical use. Precautions must be taken with implanted and superficial ferromagnetic materials of the patient or in the immediate vicinity of the magnetic field. Published data indicate that although aneurysm clips may be dangerously disturbed, many other types of surgical clips and prostheses may be safely imaged. Cardiac pacemakers are a contraindication to MRI, and careful consideration should be exercised before imaging a viable pregnancy (159, 162). The available data on long-term exposure to electromagnetic phenomena of the magnitude employed in MRI have revealed no apparent health risks. Although long-term effects might conceivably appear in the future, there is no current indication of their nature or probability.

Overall, most studies of MRI have compared it with radiographic procedures, many of which have required parenteral contrast agents. The exception has been comparison with sonographic imaging. Murphy editorialized on the difficulty of selecting a basis for judgment in Radiology (165). He commented that although evaluations of MRI have implied that it must exceed the capacities of CT to be considered favorably, it might be more appropriate to acknowledge situations in which MRI can equal CT scanning. He questioned the implication that CT is the sole significant challenge faced by MR. Many other conventional imaging studies, which often require invasive procedures, may be compared with MRI. Thus, equating image display characteristics without regard for risks due to ionizing radiation and pharmaceuticals becomes problematic. When equivalent diagnostic information may be obtained without invasive risk, image pictorial quality per se becomes secondary. This factor is of particular importance in children and young adults in whom cumulative radiation exposure should be minimized.

Evaluative methodologies have been proposed to determine the clinical efficacy of imaging technologies, but they have rarely been applied comprehensively (24,175,176). Despite much public concern over the introduction of CT, there is little information about its ultimate consequences, either economic or epidemiologic. Although clinical algorithms that guide patients to an appropriate imaging modality have been suggested, there is no precise documentation of remediable systematic flaws in current referral processes. Any such arrangement to promote efficiency and to reduce unneeded diagnostic procedures remains speculative and unstudied. In the absence of mechanisms that might routinely relegate each patient and imaging modality to an optimum plan of screening, diagnosis, and therapy, we are left with the clinical judgments of practitioners who are skilled in the use and interpretation of such examinations. In accord with the projections of DiMonda, it may be expected that MRI will substitute for existing, invasive, diagnostic imaging procedures in some patients, but will only serve to provide supplemental information in others. Diffusion of MRI may in large part be constrained by economic uncertainties about capitalization and the relatively low throughput capacity of available devices, rather than controlled access by means of diagnostic algorithms (181).

In 1984 the American College of Radiology (ACR) issued a report of its Commission on Magnetic Resonance titled Clinical Applications of Magnetic Resonance Imaging, which represented a consensus of leaders in the field of MRI. It stated, "The Commission on Magnetic Resonance Imaging of the American College of Radiology recommends that proton magnetic resonance imaging be recognized as a standard imaging modality for the diagnosis of human disease." MRI was found to be "an effective diagnostic modality for the diagnosis of disease in many anatomic sites and regions of the body." It was stated to be "equal or superior to other imaging modalities in a wide range of clinical applications," while no biological effects have been demonstrated within FDA operational parameters of commercially available units. The avoidance of ionizing radiation and intravascular iodinated contrast media are cited as advantages of MRI. Specific applications of MRI were offered as examples of its diagnostic utility, with the caveat that applications were expanding apace with scientific knowledge and physician experience. The list is as follows:

1. Brain, Head, and Neck: All diseases for which a diagnostic imaging modality is appropriate, including primary and secondary neoplasms including acoustic neuroma; pituitary gland disease; infarction/traumatic injuries; congenital abnormalities of the brain including lesions of the craniocervical junction such as Chiari malformations and hydromyelia; vascular malformations; degenerative and demyelinating disease; detection of transependymal absorption of cerebrospinal fluid in the evaluation of hydrocephalus; determination of the course of myelination; trauma to the base of skull and facial bones; disease of the neck; and diseases of the orbits. (Images of the orbits produced by recent developments in surface-coil technology demonstrate anatomic detail unparalleled by other imaging modalities. Demonstration of this technology to diagnosis of diseases of the orbit is considered imminent.)

2. Spine and Spinal Cord: Spinal cord trauma, tumors, degenerative disease of the spinal cord; hydromyelia; focal spinal and disc-space infections; congenital abnormalities; basilar invagination; C1-C2 subluxation; and degenerative diseases (including degeneration of intervertebral discs).

3. Thorax: Applicable for the differential diagnosis of vascular and nonvascular mediastinal masses.

4. Abdomen: Evaluation of abnormalities of the large abdominal vessels,

including determination of size and encroachment by tumor; diagnosis of venous or arterial thrombosis.

5. Pelvis: Diagnosis and staging of infiltration pelvic neoplasms in both male and female patients; evaluation of malignant lymph nodes in the pelvic and retroperitoneal regions.

6. Skeletal System: Diagnosis of aseptic necrosis, particularly of the hips, detection of osteomyelitis, and determination of extent and staging of soft tissue and bone neoplasms in the extremities.

The chairman of the Medical Advisory Board, National Multiple Sclerosis Society, has stated "that experience with MRI is now sufficient to assure that it is a safe procedure for use in multiple sclerosis. Furthermore, the clinical effectiveness far surpasses earlier procedures and has greatly expanded our understanding of the pathogenesis of the disease." Particular emphasis was placed on the significant clinical use of MRI "to confirm the diagnosis of multiple sclerosis in cases having a slow evolution of the classical signs and symptoms."

The American Academy of Otolaryngology-Head and Neck Surgery has recommended "a shift to MRI in appropriate clinical situations." Particular applications are cited in the diagnosis of acoustic neuroma as well as sinus and sino-orbital masses. Because of the absence of ionizing radiation, the utility of MRI in children and patients requiring repeated radiologic studies is noted. The capability of image construction in three planes and the absence of a need for injectable contrast media are additional advantages.

Comments received from the American College of Medical Physics stress that "continued physics support will produce significant improvements in imaging capability, information-content, and safety." The support of qualified medical physicists in the implementation and application of MRI was suggested to improve patient benefits and overall efficiency.

The Executive Board of the American Academy of Neurology has endorsed the position that neurologists should become proficient in the operation of MRI equipment and in the interpretation of MRI scans. The board affirmed that "neurologists are trained in pathophysiology, neuropathology, neurochemistry, neuroanatomy, and interpretation of other imaging procedures related to neurologic disease, and are ideally suited for interpretation of MRI data." Because a high degree of neurological knowledge is required to interpret MR images, "it is the position of the American Adacemy of Neurology that neurologists should decide which imaging techniques patients need for neurologic diagnosis." The Academy further recommended that appropriate training in neuroimaging be incorporated into neurological residency training programs.

As of July 1985 the FDA had approved the MRI devices of six companies for market in general interstate commerce. Five manufacturers were approved to market devices to image the head and the body, one was approved to image only the head and neck. The static magnetic field strengths of these approved devices range between 0.15T and 1.5T. In April 1985 General Electric recieved approval for cardiac gating and in May 1985 Diasonics recieved approval for cardiac and respiratory gating.

> The NMR device provides images of the internal structure of the head or body that correspond to the distribution of hydrogen nuclei (protons) exhibiting nuclear magnetic resonance. The images depend upon NMR parameters (spin-lattice relaxation time (T1), spin-spin relaxation time (T2), proton density, and flow rate) and when interpreted by a trained physician, can yield information useful in the determination of a diagnosis.

FDA adopted guidelines for the evaluation of electromagnetic risk for trials of clinical

MRI systems in 1982, and all approved devices fall within suggested parameters (156). No MR surface coils or paramagnetic contrast agents have received premarket approval.

MRI was reviewed by the National Institutes of Health (NIH) between July 1984 and July 1985. NIH informed the Office of Health Technology Assessment that, despite the large number of publications on MRI, statistically significant data to support the efficacy of this technology are not yet available but are developing. The preparation and completion of blind and double-blind studies to compare it with other imaging modalities were estimated to require considerable time. However, even without statistically sound data, MRI was viewed as superior to existing modalities in certain situations. The latter is especially true with respect to the central nervous system. Further, the use of magnetic resonance spectroscopy correlated with imaging for specific tissue identification holds great promise.

Current clinical indications for MRI as of July 1984 included the following: cerebral and spinal white-matter disease; posterior fossa tumors; pathology of the cervical cord and possibly other segments of the spinal cord dependent on the resolution of the particular MR imager (not including herniated or prolapsed intervebral discs); malignant tumors of soft tissues, lesions of large vessels such as aorta; determination of bone marrow involvement in malignant bone tumors; organs affected by iron overload; and confirmation of some pathological conditions of the heart if the imager is equipped with cardiac gating. According to NIH, the most significant advantages of MRI over other modalities were its superior differentiation of tissues in the brain with promise of similar differentiation in the body and its noninvasive character, together with the absence of ionizing radiation. Further, contrast enhancement of tissue is possible without the use of injectable contrast media. In contradistinction NIH noted the significant morbidity with low mortality associated with the currently used radiologic contrast agents and cited ultrasound as the only other modality that creates images without ionizing radiation. Because the biophysical principles of MRI differ from those of other imaging technologies, NIH considered it necessary for medical and paramedical staff to have significant additional training.

The disadvantages of MRI cited by NIH included the expense and space required to purchase and install the MRI equipment; lengthy acquisition time; effect on claustrophobic patients; inability to examine acutely ill patients; and risks in patients with pacemakers and ferromagnetic surgical clips at certain sites. NIH noted that MRI findings, particularly in the body, are in the investigative stage and much is still to be learned, especially regarding tissue differentiation.

Historically, the rapid clinical application of MRI to head scanning was attributed to the small bore of early magnets, the ability to immobilize the head and avoid blurring, the homogeneity of smaller magnetic fields, and the fact that certain intracranial diseases were particularly amenable to MR diagnostic imaging. In body scanning, the ability to image in sagittal, coronal, transverse, or oblique cross-sectional planes as well as the capability for multislice imaging were considered to be advantages. Furthermore, the ability to vary contrast and other imaging parameters noninvasibely to optimize the image for specific diseases was favorably mentioned, as was the possibility of repeat images without hazard, to monitor therapy. According to NIH, although throughput was about 7 to 10 patients per 8-hour shift, improvement might be expected with development of equipment and facilities that would permit more efficient handling. By the latter half of 1984, NIH reported that virtually all parts of the body had been surveyed with MR imaging. Although useful applications had been reported and case comparisons with other modalities drawn, NIH found these comparisons to be subjective without precise standards. Valid conclusions about appropriate applications of MRI were thus rendered difficult. Although cardiovasuclar studies with MRI are attainable, their clinical utility was considered unproven. NIH now supports a number of intramural and external MRI clinical imaging studies, ranging from investigations of T1 and T2 tissue-specific relaxation times, to functional circulatory flow studies, anatomic imaging of specific lesions, spectroscopy, and spectroscopic imaging. Developmental work on improvements in MR technology is also underway.

SUMMARY

Magnetic resonance imaging (MRI) is a noninvasive method of graphically representing the distribution of water and other hydrogen-rich molecules in the human body. It is based on the magnetic properties of protons that spin and act as magnetic dipoles. When the human body is placed in an electromagnetic field of sufficient magnitude, the minute "hydrogen proton magnets" tend to align with the external field. When a second magnetic field is applied at an angle to the first, the protons will tend to assume a new alignment at a higher energy state. With dissolution of this second field, the protons will return to their original alignment distribution, releasing energy in the form of a radio frequency (RF) signal. Once these RF signals are received and processed by means of a computer, a graphic image can be constructed that will represent the substance being examined and the environment surrounding it.

The potential imaging capability of MRI is high when compared with the capabilities of other imaging modalities such as computed tomography. At least five tissue characteristics can be studied by MRI: proton density, spin-lattice relaxation time (T1), spin-spin relaxation time (T2), fluid flow, and spectral shifts. Measurements of these characteristics may be combined in accordance with different computerized image reconstruction algorithms to produce variations in image appearance that may emphasize contrast differentiation between tissues. In general, T1 contributes to structural distinctions while T2 aids tissue distinctions. Other nuclei besides protons have been imaged, but such efforts remain investigational, as does the in vivo MR spectroscopic analysis of chemical compounds in tissue.

Because imaging parameters are complex, medical applications of MRI technology require an understanding of data acquisition principles coupled with the clinical skills that enable a practitioner to interpret an image in relation to the signs and symptoms of

a specific patient. Pulsing sequences must be selected so that pathology is revealed with efficacy and efficiency. This involves the ability to match MRI techniques to the biophysical properties of the lesion being sought with reference to the probable effects of its anatomic environment. Thus, although MR images may demonstrate anatomy much as do conventional radiographic or CT modalities, the basis of the images and their information content are quite different. In addition to having the traditional cognitive skills necessary for understanding the localization and manifestations of disease, medical and paramedical professionals engaged in clinical MRI must undergo extensive specific training.

MRI is without demonstrable adverse biological effects when commercially marketed systems are operated within the parameters specified in their premarket approval by the FDA. Caution must be exercised with patients having metallic surgical clips or prostheses. The presence of cardiac pacemakers or metallic clips on vascular aneurysms is generally considered a contraindication for MRI. MRI during a viable pregnancy is also considered by many authors to be contraindicated at this time because of a lack of adequate data, although some investigators have used diagnostic MRI after the first trimester. Ferromagnetic objects on the patient or in the vicinity of strong magnetic fields may become hazardous missiles. This factor has constrained the use of MRI in acutely ill patients requiring life-support equipment and monitoring devices. Nonmagnetic substitutes have now been developed for many situations. The long imaging time required by MRI in relation to other procedures, together with the enclosed patient position within the magnet bore, has led to claustrophobia in a small percentage of cases. Adequate patient preparation for the experience of MRI has been reported to reduce this effect.

The principal disadvantages of MRI at this time generally involve the cited difficulty in obtaining and interpreting non-radiographic data, as well as the expense of purchasing and installing MR equipment. The extended length of time required for each examination has generally limited productivity to about 6 to 10 patients per 8-hour shift, but improved procedural efficiencies may increase this throughput capacity. Cortical bone, calcifications, and moving objects are not well visualized with MRI, and its spatial resolution does not yet equal that of high-resolution CT and radiology.

Among the advantages of MRI, absence of ionizing radiation and the ability to achieve high levels of tissue contrast resolution without injected iodinated contrast agents are predominant. Multislice imaging and the ability to image in multiple planes, especially sagittal and coronal, have provided a modicum of flexibility not easily available with other modalities. Because cortical bone and metallic prostheses do not cause distortion on MR images, it has been possible to visualize certain lesions and body regions with greater certainty than has been possible with CT.

Research is under way on the potential of MRI to measure blood flow, characterize tissue by its relaxation times, and to improve image conspicuity with paramagnetic contrast materials, and on the use of cardiac or respiratory gating for heart and lung studies. These procedures are all considered investigational at this time, as are all procedures that employ surface coils to send or receive pulses.

Scientifically controlled comparative evaluation studies in clinical MR imaging are not yet available, but such studies have not been a significant factor in the introduction and diffusion of other imaging modalities, possibly because they are time-consuming ventures that constrain access to perceived patient benefits. MRI will undoubtedly be the subject of continuing assessment, but proton imaging of certain soft-tissue structures for the purpose of detecting disruptive, neoplastic, degenerative, or inflammatory lesions has now become established in medical practice.

MRI has found its greatest utility in examining the head, central nervous system, and spine. Because multiple sclerosis can be diagnosed rapidly and efficiently with MRI and the contents of the posterior fossa are uniquely visible, these applications have received considerable attention. Nevertheless, the inherent tissue contrast-resolution of

MRI makes it an appropriate standard diagnostic modality for general neuroradiology when employed by trained practitioners. Although degeneration of intervertebral discs can be detected, the role of MRI in diagnosing disc herniation or prolapse remains uncertain. But when sensitivity to contrast agents exists and their use is contraindicated, MRI may be the only alternative to myelography.

Reported use of MRI for body imaging has been more limited than for CNS applications. Nevertheless, rational use in experienced hands appears to be efficacious. MRI can assist in the differential diagnosis of mediastinal and retroperitoneal masses including abnormalities of the large vessels such as aneurysms and dissection. When a clinical need exists to visualize the parenchyma of solid organs to detect anatomic disruption or neoplasia, this can be accomplished in the liver, urogenital system, adrenals, and pelvic organs without the use of contrast materials. The availability of coronal and sagittal views, in conjunction with high levels of tissue contrast and good definition of vasculature, has enhanced the clinical utility of MRI for these applications. It has also been possible to detect and stage pelvic and retroperitoneal neoplasms. MRI has been used effectively to evaluate disorders of cancellous bone and soft tissues.

Primary and secondary bone neoplasms and aseptic necrosis can be detected at an early stage and monitored with MRI. Metallic prostheses, especially of the hip, can be successfully depicted with some signal loss, but minimal artifact, to detect the early stages of infection.

Overall, MRI is a useful diagnostic imaging modality that is capable of demonstrating a wide variety of soft-tissue lesions with contrast resolution equal or superior to CT scanning in various parts of the body. The most efficacious clinical applications of MRI result from the selection of appropriate pulse sequences and data acquisition modes with respect to the characteristics of the tissue being examined. In experienced, trained hands, a decision to employ MRI for anatomic imaging should be made for a specific diagnostic purpose within the capability of the modality to represent the particular information being sought. Such clinical judgments might include consideration of radiation risks and the relative hazards of contrast agents required for alternative imaging modalities.

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16. Abstract (Limit: 200 words)

Magnetic resonance imaging (MRI) is a method of graphically representing the distribution of water and other hydrogen-rich molecules in the human body. Imaging parameters are complex. Although MR images may demonstrate anatomy as do conventional radiographic or CT modalities, the basis of the images and their information content are different. MRI is without adverse biological effects when commercially marketed systems are operated within the parameters of their premarket approval by the FDA. The absence of ionizing radiation and the ability to achieve high tissue contrast resolution without injected contrast agents are advantages of MRI. Multislice and multiplane imaging, especially sagittal and coronal, have provided flexibility not easily available with other modalities. The tissue contrast-resolution of MRI makes it an appropriate diagnostic modality for general neuroradiology. Use of MRI for body imaging has been more limited than for CNS applications. MRI can assist in the diagnosis of pericardial constriction as well as mediastinal and retroperitoneal masses including abnormalities of large vessels. The parenchyma of solid organs can be examined and it has been possible to detect and stage pelvic and retroperitoneal neoplasms and to evaluate disorders of cancellous bone and soft tissues.

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107